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When mulch burns: fire risks at the wildland–urban interface

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ABSTRACT

Background. Mulch is widely used for landscaping in wildland–urban interface (WUI) communities but can act as a fuelbed that facilitates fire spread from vegetation to structures. **Aims.** Although prior laboratory studies have investigated mulch ignition thresholds, few have examined large-scale burning dynamics under outdoor conditions representative of real wildfire exposure. **Methods.** Full-scale fire tests were conducted on 10 weathered mulch products, including 5 composted and 5 non-composted types. **Key results.** Non-composted mulches can sustain flaming combustion, exhibiting faster fire spread, greater flame heights, and higher heat fluxes compared to composted mulches. Composted mulches generally produced weak or unstable flames, transitioning rapidly to smoldering combustion, which slowed fire spread. In some tests, ignited particles driven by wind roll across the fuel surface and ignite adjacent fuel. Particle size influences burning behavior, with mulch made of larger fir bark particles sustaining more vigorous flame spread vs smaller particles that primarily smoldered. **Conclusions.** Comparison with prior small-scale studies confirmed that while laboratory experiments capture ignition thresholds, only large-scale testing revealed ember spotting, sustained flaming spread, and heat flux exposures. **Implications.** These findings provide empirical evidence to guide defensible space design, mulch selection, and fire risk reduction strategies in wildfire-prone WUI communities.

Keywords: defensible space, ember, firebrand, ignition, mulch, spotting, wildland-urban interface, WUI.

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Introduction

The wildland–urban interface (WUI) refers to the zone where urban development meets or intermingles with natural vegetation and is at risk from fires spreading (Mell *et al.* 2010; Koksal *et al.* 2019; Schug *et al.* 2023; Chen *et al.* 2024; Qiu *et al.* 2025). These areas are increasingly becoming a focal point of concern due to the growing threat of wildfire (Manzello and Foote 2014; Caton *et al.* 2017; Manzello and Quarles 2017; Hakes *et al.* 2017; Manzello *et al.* 2020; Schug *et al.* 2023; Zamanialaei *et al.* 2025). As urban sprawl expands into previously wildland areas, the risk of wildfire spread from wildland to structures increases, with potentially devastating consequences for both lives and property (Mell *et al.* 2010; Manzello 2014; Suzuki *et al.* 2014; Fernandez-Pello 2017; Manzello and Quarles 2017; Wadhwani *et al.* 2022; Zamanialaei *et al.* 2025). Homes in the WUI are particularly susceptible to fire risks due to their proximity to flammable vegetation, combined with the presence of combustible building materials (Nam and Bill 2009; Song *et al.* 2014; Richter *et al.* 2022). Notable examples of WUI fires include the 2018 Camp Fire, which destroyed the town of Paradise, California, USA (CAL FIRE 2020), and the 2019–2020 Australian bushfires (Deb *et al.* 2020), which devastated communities across New South Wales and Victoria. More recently, the January 2025 fires in the Los Angeles area of California have destroyed over 16,000 structures (Qiu *et al.* 2025) (Fig. 1*a*). In all cases, fire spread rapidly from wildland areas into suburban areas, overwhelming fire fighting efforts and causing extensive

Collection: Wildland-Urban Interface Fires: Lessons Learned, Future Challenges, and Pathways Forward damage (Mell et al. 2010; Caton et al. 2017; Schug et al. 2023). To mitigate fire losses at the WUI, a range of strategies have been employed, including the creation and maintenance of defensible space (Braziunas et al. 2021), where fire-resilient landscaping techniques are used to limit fire spread to structures, as well as the retrofitting of buildings with fire-resistant materials (Zipperer et al. 2007; Hakes et al. 2017; Lin et al. 2023). Similarly, vegetation management in areas surrounding communities is promoted to reduce the likelihood or intensity of fire entering residential areas. However, despite an overall decline in global burned area during the same period, large outdoor fire incidents at WUI have grown disproportionately compared to global wildfire trends. Between 2005 and 2020, the number of WUI fires occurring increased by approximately 20–25%, while the burned area rose by more than 30% (Tang et al. 2024; Guo et al. 2025). These trends necessitate further research into WUI fire behavior to enhance mitigation strategies and improve fire resilience.

Wood and bark-based mulch products, widely used organic materials in landscaping, play an important role in the landscape as they help with soil moisture retention, weed suppression, and erosion control (Steward et al. 2003; Quarles and Smith 2011). Mulch is often spread around residential homes, in parks, and in public spaces due to its aesthetic appeal and functional benefits (Quarles and Smith 2011) (Fig. 1*b*). However, these combustible mulch products pose a significant hazard in WUI environments (Manzello et al. 2006; Zipperer et al. 2007; Orgstad et al. 2011; Quarles and Smith 2011; Beyler et al. 2014; Ellis 2015; Manzello et al. 2017; Hsieh et al. 2019; Wadhwani et al. 2022; Lin et al. 2025). Mulch, particularly when it becomes dry or is applied in thick layers, can easily ignite from embers carried by the wind during a wildfire (Manzello et al. 2006; Koo et al. 2010; Caton et al. 2017; Lin et al. 2024). This can lead to the rapid spread of fire from the mulch to nearby structures, presenting an effective pathway for fire to ignite homes and other buildings (Caton et al. 2017). Additionally, the presence of mulch can exacerbate the fire's intensity, as the material provides a continuous fuel source, allowing the fire to persist longer and spread. Given the prevalence of mulch in WUI areas, it is crucial to better understand its fire behavior, yet there remains a gap in research on quantifying the fire risk of mulch in these settings. Addressing this gap is important for developing more effective fire mitigation strategies and improving the safety of communities at risk from WUI fires.

Although several studies have explored the ignition characteristics and fire behavior of mulch under laboratory conditions, these experiments have often been conducted at small scales or in highly controlled environments that may not accurately represent the complexities of real-world fire scenarios (Steward et al. 2003; Manzello et al. 2006; Zipperer et al. 2007; Orgstad et al. 2011; Quarles and Smith 2011; Weir et al. 2015; Caton et al. 2017; Hsieh et al. 2019; Lin et al. 2025). Some studies have investigated the impact of different types of mulch and levels of moisture content on ignition and burning duration, while others have modeled the spread of fire. For example, Steward et al. (2003) performed experiments on 13 different mulches to measure their relative ease of ignition when exposed to a lit cigarette, match, or propane torch. The results demonstrated that while all fuels could ignite under direct flame exposure, only some could be ignited by cigarettes or matches. Similarly, Zipperer et al. 2007 used a drip torch for ignition to evaluate the relative flammability of several mulch types and concluded that almost all organic mulches are flammable when exposed to direct flames. Regarding firebrand (ember) exposure, Manzello et al. (2006) found that the ignition propensity of three types of mulch increased with the size of the deposited firebrand, emphasizing the critical role of contact between firebrands and mulch beds. Manzello et al. (2006, 2017) further highlighted that the ease of ignition increased with the number of firebrands, underscoring the importance of studying the accumulation of brands rather than just individual particles.

In our previous work (Lin et al. 2024), we quantified the thresholds for smoldering ignition of four common types of commercially available mulch when exposed to heating by smoldering firebrand piles. We identified a minimum mass of firebrand pile required to achieve smoldering ignition and observed that smoldering-to-flaming transition occurred when a wind speed exceeded a critical value. Afterwards, we further quantified the ignition thresholds of 10 landscaping mulches commonly used in Marin County, California, including composted (bioretention, Caltrans, Marin Vineyard, topper mulch, screened compost) and non-composted (forest floor, redwood, black mulch, fir bark A [large pieces] and fir bark B [small pieces]) types, exposed to smoldering firebrand piles and irradiation (Lin et al. 2025). We found that all mulches except screened compost can be ignited in a smoldering mode by glowing firebrand piles within the test range. Furthermore, the required wind speed for smoldering ignition decreased as the mass of the firebrand pile increased. Following spotting ignition, non-composted mulches were more prone to smoldering-to-flaming transition at critical wind speeds, which varied between mulch types but were insensitive to the initial spotting process. For piloted flaming ignition, all mulches can sustain flames under irradiation, with non-composted mulches generally requiring lower critical heat fluxes due to the emission of more combustible gases during pyrolysis. Particle size significantly influenced ignition thresholds, with smaller particles facilitating piloted flaming ignition and larger particles being more susceptible

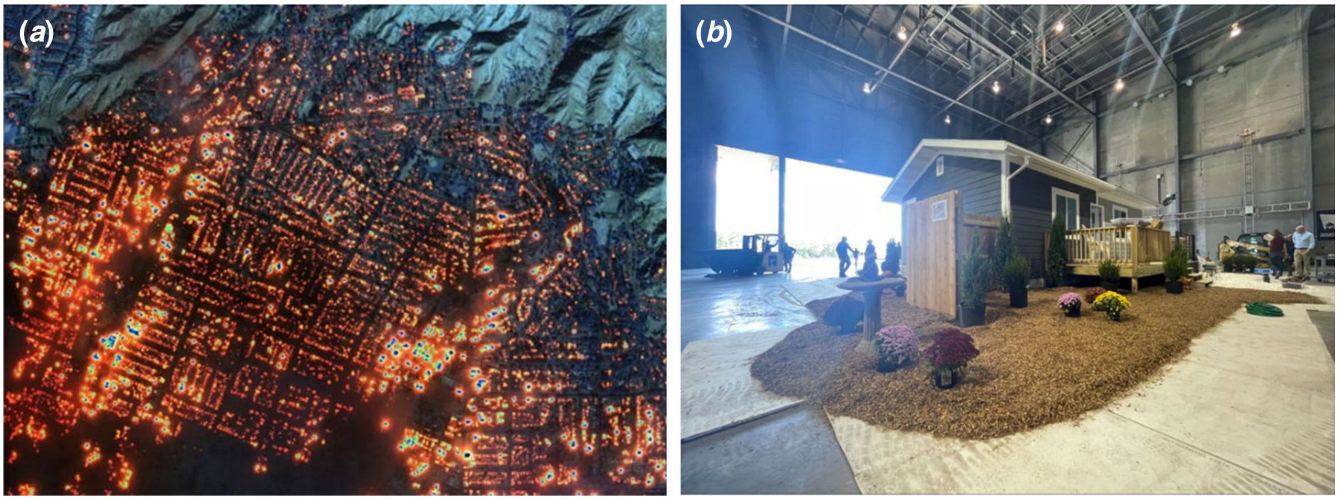

Fig. 1. (*a*) Nighttime satellite image showing wildfire burning homes and buildings in the Altadena region, Los Angeles County, on 8 January 2025 (Source: Maxar Technologies); and (*b*) photograph showing landscaping mulch around a simulated structure used for WUI fire testing (Source: Insurance Institute for Business & Home Safety).

to firebrand-induced smoldering ignition and subsequent smoldering-to-flaming transition.

However, very few of these studies addressed the fire dynamics occurring in large-scale, uncontrolled environments, such as those encountered during significant wildfires in the WUI. The lack of large-scale experimental data on mulch fires leaves critical uncertainties in our understanding of how mulch behaves during wildfires, which limits the development of accurate predictive models and effective fire mitigation strategies. In 2008, an evaluation of mulch combustibility using 8-foot (2.4 m) diameter plots was performed in Carson City, NV, USA (Quarles and Smith 2011). This study followed the general experimental design of Zipperer *et al.* (2007), which identified flammability characteristics of pine straw, pine bark, and shredded cypress mulch. Building upon these earlier efforts, there remains a need to further investigate a wider array of mulch fire behavior under diverse, representative WUI conditions to strengthen the scientific basis for fire risk assessment and mitigation planning.

The goal of this study was to conduct large-scale fire tests in Marin County, a region that is representative of many WUI areas across the western United States. Marin County, known for its susceptibility to wildfires due to its mix of wildland areas and residential communities, provided an ideal location for investigating the fire dynamics of mulch in WUI environments. The large-scale tests simulated real-world wildfire scenarios and enabled a detailed examination of how mulch ignites, how fire spreads through mulch, and how it might expose surrounding vegetation and structures. By providing much-needed empirical data on mulch fire behavior in the WUI, this research will contribute to the development of more accurate fire risk models and better fire prevention strategies. The results will inform fire safety regulations, guide landscaping practices, and ultimately help reduce the vulnerability of communities at the WUI to wildfire hazards.

Experimental details

Mulch samples

A coalition of agencies, industries and scientific organizations partnered to conduct a scientific study to evaluate the relative flammability of various mulch products in Marin County. Ten mulch products were used in this experiment. Five were composted (a product that has been set out in a pile that was regularly turned and allowed to decompose to some extent) and five were not composted (see Fig. 2, where an aerobic windrow composting process was used to produce the composted products).

Seven of the products were sourced in Marin County (see photos in Fig. 3). Three of the composted products were sourced from the San Jose, California area. Non-composted products included: redwood chip (RW), fir bark (FB), forest floor (a proprietary wood/bark formulation combined with trimming or waste, FF) and black mulch (BM). The composted mulch products included two from West Marin Compost (Nicasio, CA), Marin Vineyard (MV) and Topper (tree) Mulch (TM), and three from Z-Best/GreenWaste (San Jose, CA), bioretention (BR), Caltrans (CT) and screened compost (SC). The particle size distribution was determined by passing the mulch samples through a series of sieves with gradually reducing hole sizes, and the results are shown in Fig. 3*b*.

The volatile fraction of the mulch sample was measured as the weight percent of gas (emissions) from the mulch sample during heating to 800°C at a rate of 30°C/min

Fig. 2. Windrow composting at West Marin Compost, Nicasio, CA. USA.

in an oxygen-free environment using a PerkinElmer STA 6000 Simultaneous Thermal Analyzer. A C/H/N elemental analysis was also performed using a Thermo Fisher FlashSmart Elemental analyzer. The physical properties of the mulch samples are summarized in Table 1. It is noted that large fir bark A (more large particles) and fir bark B (more small particles) have the same physical properties except for the particle sizes, allowing the effect of particle size to be explored.

Experimental procedure

Mulch products were arranged into circular piles with a diameter of 8 feet (~2.4 m) and an initial nominal thickness of 3 inches (~7.6 cm), placed in an outdoor test field on the site of the former San Geronimo golf course, and current home of the Marin County Fire Department Headquarters station in San Geronimo (see Fig. 4). Each pile was separated by a minimum distance of 8 feet (~2.4 m) to reduce the chance of interference between plots. To track fire spread, steel rebars with alternating white-painted 6-inch (~15 cm) sections were installed (Fig. 5). One rebar was positioned vertically at the pile center, while two additional rebars were placed 2 feet (~0.61 m) away on either side, forming a straight line of three markers. These rebars served as fixed reference points to quantify the rate of fire spread and serve as a reference scale in recorded videos. Two further locations, also 2 feet (~0.6 m) from the center rebar, were designated for post-burn sampling to determine the depth of consumption. A fully consumed pile was recorded as having zero residual mulch depth. For the combustion experiments, the mulch materials were used in their as-received condition without pre-sieving. Sieving was only applied separately for particle size distribution measurements and was not used as a preprocessing step for fuelbed preparation.

Ignition was facilitated using a U-shaped bent wire (horizontal span 2.5 feet (~0.76 m), see Fig. 5), with its

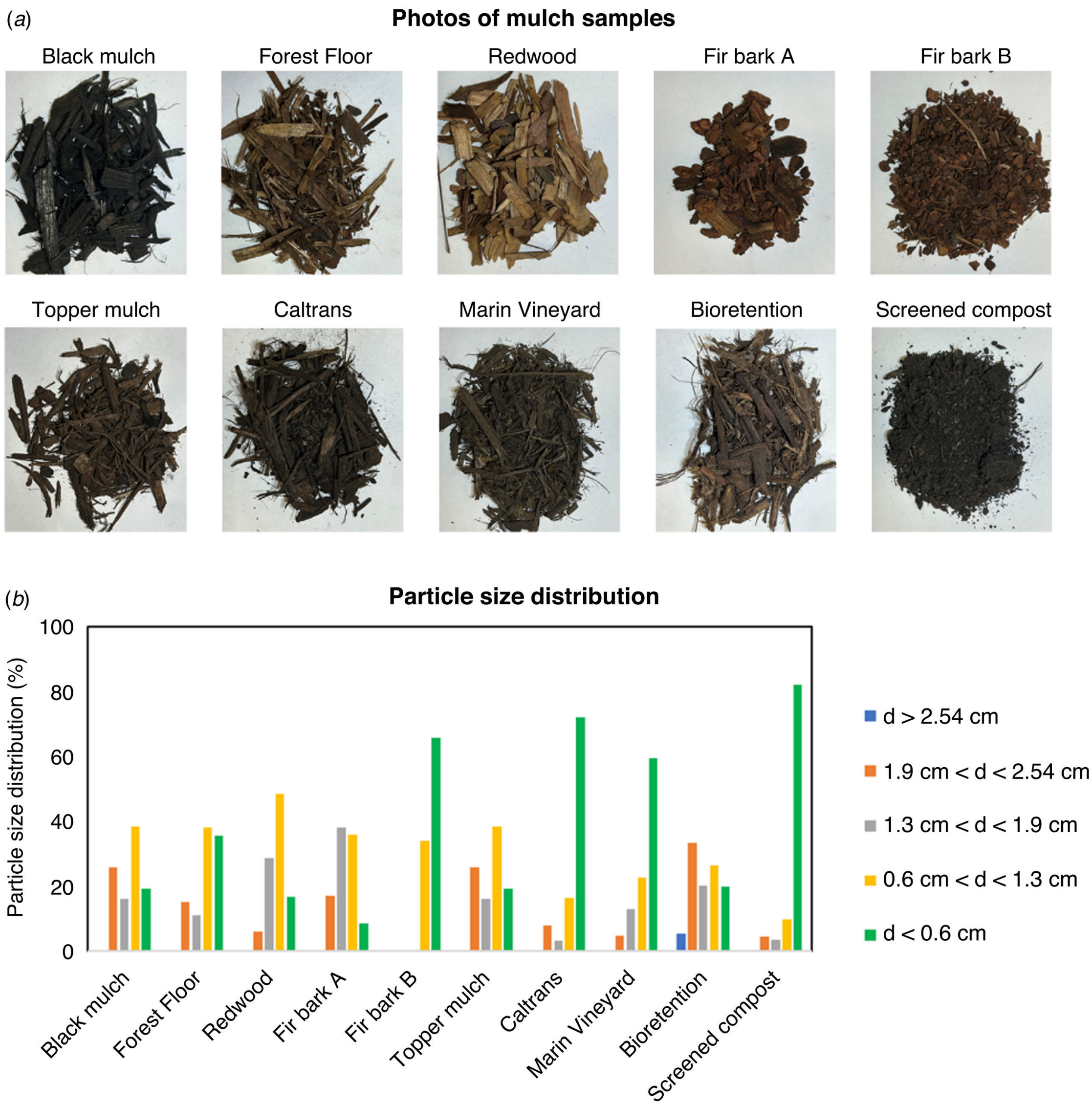

Fig. 3. (*a*) Photos of non-composted (upper row) and composted (lower row) mulch samples, and (*b*) particle size distributions of the mulch samples tested in this study (Lin *et al.* 2025).

vertical prongs inserted into the mulch bed to mark the ignition line. Two 12-inch-diameter fans were placed 2 feet (~0.61 m) from the pile edge, adjacent to the ignition line, to provide forced wind conditions. Wind speed was highly variable depending on ambient conditions and specific fan placement but ranged on the order of 4 ± 1 m/s at the leading edge of the plot to 2 ± 1 m/s at the center of the plot measured with a handheld hot wire anemometer aligned with the fan before the fire test. On the opposite side of the mulch bed, a fire behavior package including an uncooled total heat flux sensor, radiometer, thermocouple, and bi-directional probe was positioned beyond the bed boundary to measure heat flux from the burning mulch ([Jimenez *et al.* 2007). The package was similar to those used previously to measure wildland fire behavior (Butler *et al.* 2010) and utilized the same calibration and processing steps used previously. Note the heat flux gauge was positioned 1 ft (~30 cm) in front of and ~4.6 inches (11.8 cm) above the leading edge of the mulch surface, thus providing only a single spatial measurement. Flame development was recorded by two video cameras: one oriented horizontally at 90° to the bed, and the other elevated at 45°, directed toward the pile to capture the overall burning dynamics.

The mulch products were weathered outdoors for approximately four months (June–October) to simulate conditions typical of residential yards and landscapes in Marin County (see Fig. 4*b*). Rain is rare during the summer months in this region. Prior to testing, subsamples were collected to determine moisture content on a dry basis using an A&D MF 50 moisture analyzer. Each test was ignited along the horizontal length of the U-shaped wire

Table 1. Physical properties of the mulch products, where black mulch, forest floor, redwood, fir bark are non-composted mulches, while others are composted mulches.

Mulch type	Abbreviation	Bulk density (kg/m^3)	Moisture content (%)	Volatile fraction (%)	C (%)	H (%)	N (%)
Black mulch	BM	130	8.6	86.6	46.4	6.2	0.1
Forest floor	FF	157	6.5	66.1	44.9	6.1	0.5
Redwood	RW	152	7.5	85.8	47.8	6.4	0.2
Fir bark A (large)	FBA	253	5.1	70.9	47.0	6.2	0.1
Fir bark B (small)	FBB	247	6.4				
Topper (tree) mulch	TM	188	6.6	75.2	45.8	5.8	0.4
Caltrans	CT	320	6.1	62.2	45.5	5.5	0.7
Marin Vineyard	MV	208	8.8	74.3	41.1	5.4	0.5
Bioretention	BR	236	8.6	82.8	44.4	6.0	0.6
Screened compost	SC	571	2.3	41.4	37.8	4.6	1.9

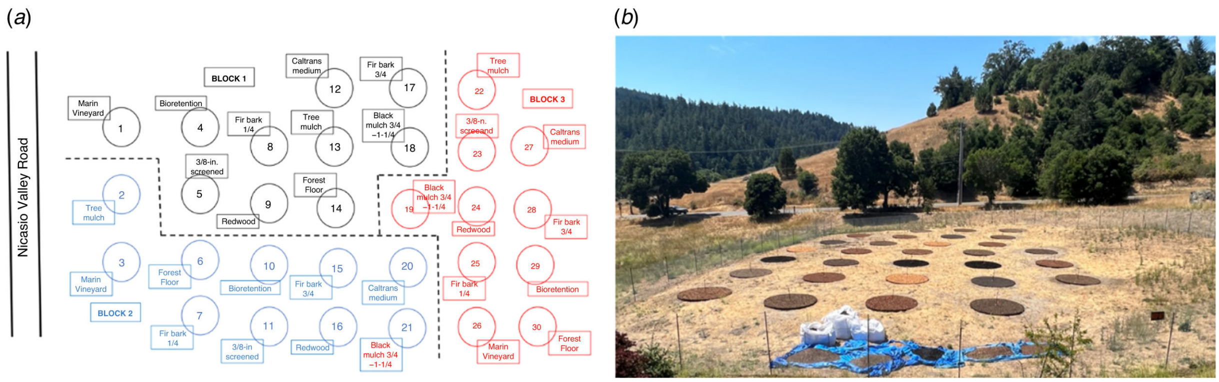

Fig. 4. (*a*) Diagram of plot layout, showing separation of test plots into three blocks, where the fractional values (e.g. 1/4, 3/4, 3/8-in, 3/4–1-1/4) denote mulch particle/chip sizes in inches, and (*b*) layout of mulch plots in western Marin County, California. Note: The plot numbering shown is independent of the experimental testing order.

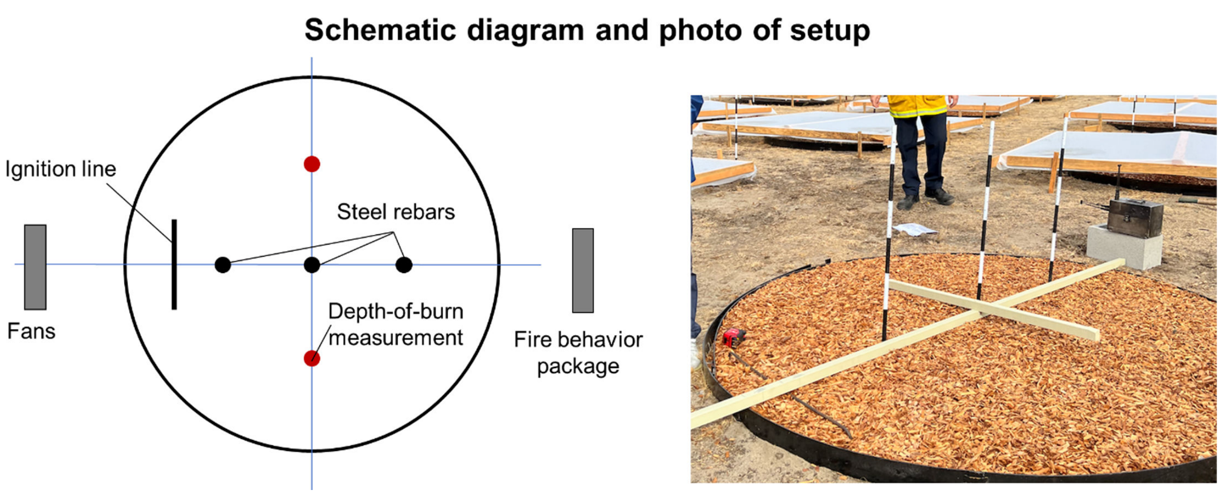

Fig. 5. Schematic diagram and photo showing the position and dimensions of the ignition line, stick, rods and fans.

using a drip torch. The experiment was terminated once the flame front reached the opposite side of the bed, all fuel was consumed, or the fire self-extinguished. Firefighters from the Marin County Fire Department were present throughout the tests to ensure operational safety.

The full burn campaign was conducted over three days in October 2023. The experimental field consisted of 30 circular test plots, each enclosed by a metal border and lined with a fine mesh screening to prevent subsurface disturbance by gophers before being filled with mulch. The field was divided into three blocks of 10 plots, with each mulch type randomly allocated to each block, ensuring that each block contained all 10 mulch products. The testing order was randomized by sequentially selecting plots across the three blocks (e.g. Block 1 → Block 2, Block 3 → Block 1, Block 2 → Block 3), until all burns were completed. Before ignition of each plot, two hand-grab mulch samples were collected to determine moisture content with an on-site moisture analyzer, and the results are summarized in Table 1.

Results

Fire behavior

With the exception of screened compost, all mulch beds were capable of igniting and supporting fire spread in a flaming mode. Non-composted mulch, including redwood, black mulch, forest floor, and fir bark generally sustained flaming combustion throughout the entire experimental process, while composted mulch would trigger flame extinguishment after some period. Although these flames would self-extinguish, smoldering-to-flaming transition was also observed, occasionally re-igniting flames. The wind speeds applied over the fuelbed also caused some ignited particles to be displaced by the wind, rolling across the fuel surface and settling in new positions, where they subsequently ignited the adjacent fuel in the same plot. This 'spotting' ignition behavior can accelerate fire spread, as the rolling hot particles can move faster than the flame or smoldering front. More details of the fire behavior of different mulch beds is provided below.

Black mulch, redwood and forest floor (non-composted)

After ignition, a vigorous and intense flame front was initially observed, rapidly propagating across the surface of the mulch beds, efficiently consuming the material as it spread (Fig. 6). The main direction of fire spread was strongly affected by the wind direction, as the concurrent fire spread was the fastest. As the flame front gradually diminished as the pyrolysis process ceased, smoldering combustion with lower temperature and slower propagation rate gradually took over. During this period, the fuel surface burned slowly, with minimal visible flames. However, smoke production became more intense compared to that of flaming phase. The material continued to degrade, with the combustion process now dominated by smoldering, and over time, the fuel was reduced to a fine and ashy residue.

Marin Vineyard, Topper (tree) mulch and Caltrans (composted)

Following flaming ignition, the flame front spread outward across the mulch products (Fig. 7). Despite its early expansion, the flame exhibited significant instability, and as a result, could only be sustained for a relatively short period. Once the flame self-extinguished, the combustion process transitioned to smoldering, which dominated the burning behavior for the majority of the experiment. However, the smoldering process was intermittently interrupted by brief episodes of smoldering-to-flaming transition. These transitions often appeared to be triggered by external factors, likely gusts of higher external winds. Furthermore, due to the light weight of the mulch particles, some of the ignited, hot particles were carried by the wind, tumbling across the fuel surface and landing in new areas, where they can ignite fresh fuel. This is similar to the spotting ignition caused by the flying embers or burning debris, which can occasionally ignite portions of the material at distant locations from the main fire front, accelerating fire spread.

Bioretention (composted)

Following flaming ignition, flaming was only able to be sustained near the ignition zone, in closest proximity to the fan and higher wind speeds (Fig. 8). This localized flame front remained concentrated, unable to extend further due to its reduced intensity as it moved away from the fan. In contrast, the fire's propagation primarily occurred through smoldering combustion, characterized by a slower solid phase burning process that spread gradually across the surface. Notably, spotting ignition, where embers or hot particles can ignite new areas at a distance, was not observed to accelerate the spread of the fire in this product. This was likely due to the larger particle size of the material (see Fig. 3*b*), which limited the ability of the fire to jump to new fuel sources, thus restricting the spread of combustion through airborne embers at the tested wind speed.

Screened compost (composted)

Screened compost was the only mulch type tested that did not transition to sustained flaming combustion under the applied heating conditions (Fig. 9). However, a weak smoldering combustion front was consistently observed within the ignition zone, indicating the occurrence of slow, low-intensity heterogeneous oxidation. This smoldering phase persisted for an extended duration and resulted in gradual, localized mass loss of the material.

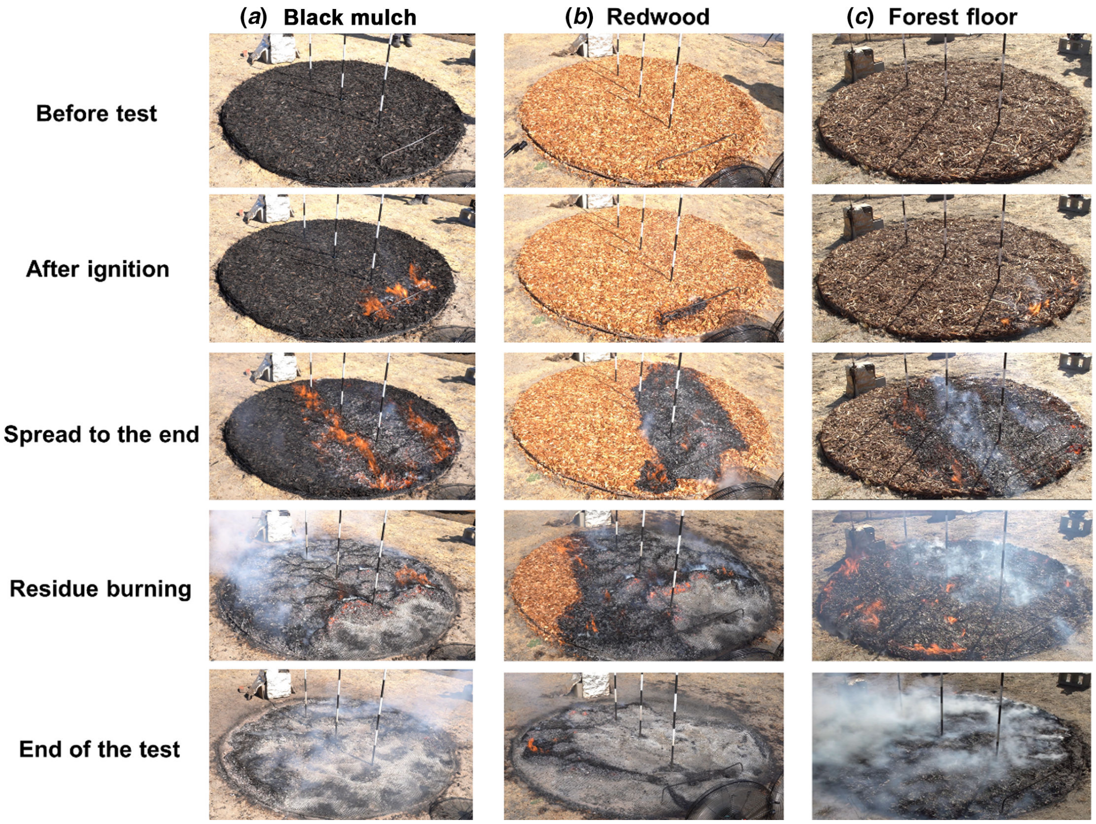

Fig. 6. Progression and key fire behavior phenomena of tests using (*a*) black mulch, (*b*) redwood and (*c*) forest floor.

The absence of flaming combustion is likely associated with the intrinsic physical and chemical characteristics of the screened compost, including its relatively higher bulk density and lower content of readily volatilizable organic compounds (see further discussion under 'Influence of mulch properties on flammability'). These properties may reduce the rate and magnitude of pyrolysis gas production, thereby limiting the formation of a sufficiently fuel-rich and heat-sustaining gaseous phase required for flame initiation and propagation.

Importantly, the presence of sustained smoldering indicates that non-flaming combustion processes can still contribute to significant thermal degradation of the fuelbed. From a fire spread perspective, such smoldering layers may act as persistent heat sources and can elevate the thermal state of adjacent fine fuels. If sufficiently dry, low-density, and flammable surface fuels (e.g. litter layers) are present in close contact with the smoldering zone, this could provide conditions conducive to localized heating and, under favorable circumstances, may facilitate a transition to flaming combustion.

Fir bark (non-composted)

For fir bark with smaller particles, once ignition occurred, smoldering combustion quickly dominated the process. However, the individual particles of fir bark underwent noticeable deformation and swelling during combustion, a behavior that was also observed in small-scale tests (Lin *et al.* 2024) (Fig. 10). Under the influence of external winds, these ignited particles could easily roll across the surface of the fuel, settling in new positions and igniting fresh fuel sources, which in turn accelerated the spread of the fire. This movement and redistribution of burning particles enhanced the fire's ability to expand and propagate. In contrast, fir bark with larger particles exhibited a markedly different behavior. Upon ignition, a strong and sustained flame front was observed, similar to other non-compost mulch types. The flame spread rapidly across the fuel surface, consuming material at a high rate. Due to the fast-moving flame, spotting ignition (where embers ignite new areas of fuel) was infrequent. Nonetheless, some hot particles were carried by the wind and, in some instances, were ejected from the pile entirely, exhibiting the potential to ignite nearby vegetation. Compared to other mulch types, fir bark posed the highest risk of spotting fires, given

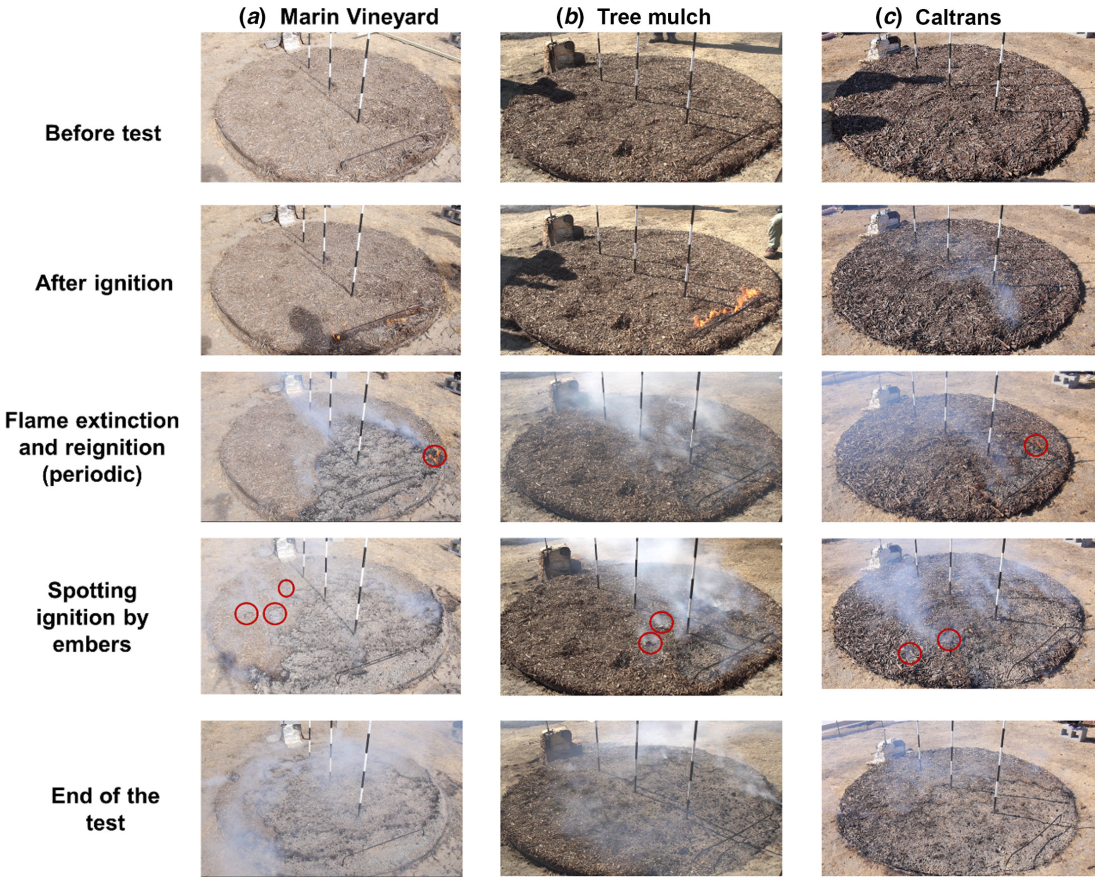

Fig. 7. Progression and key fire behavior phenomena of tests using (*a*) Marin Vineyard, (*b*) Topper (tree) mulch and (*c*) Caltrans.

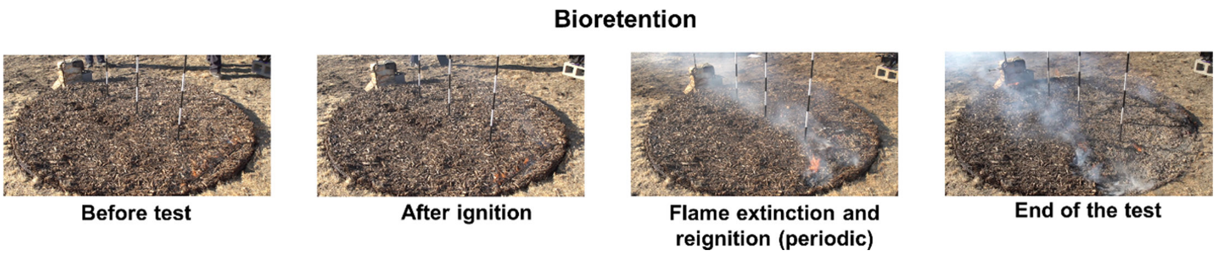

Fig. 8. Progression and key fire behavior phenomena of tests using bioretention.

its tendency to produce large, highly mobile embers that could travel longer distances and ignite new fire points.

Fire spread rate

Fig. 11 summarizes the fire spread rates of the various mulch products tested in this study. The fire spread rate is defined as the speed at which the front of the burning region expands over time, here including both the flame and smoldering fronts. It is important to note that this analysis excludes the effect of spotting ignition by embers, which could contribute to fire spread in certain circumstances but was not directly considered in this study. Additionally, the fire spread rate of screened compost was not included in the figure because, within the test conditions, the fire remained localized without propagating beyond its initial ignition area.

As illustrated in Fig. 11, the fire spread rates of non-composted mulch products tended to be higher than those of composted mulch. For instance, the fire spread rates of forest floor, redwood, and black mulch were approximately 0.73 ± 0.25, 0.89 ± 0.18, and 0.81 ± 0.37 cm/s, respectively. These rates were substantially greater than the rates observed for composted mulches such as Topper

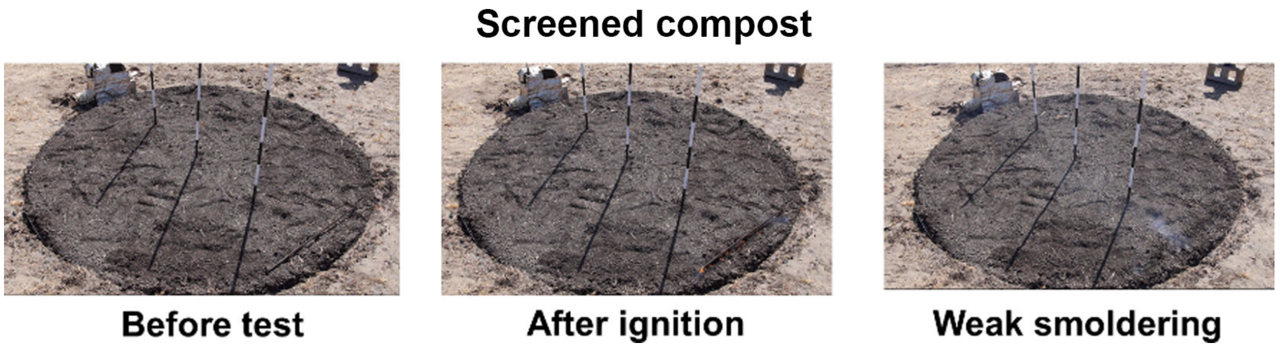

Fig. 9. Progression and key fire behavior phenomena of tests using screened compost.

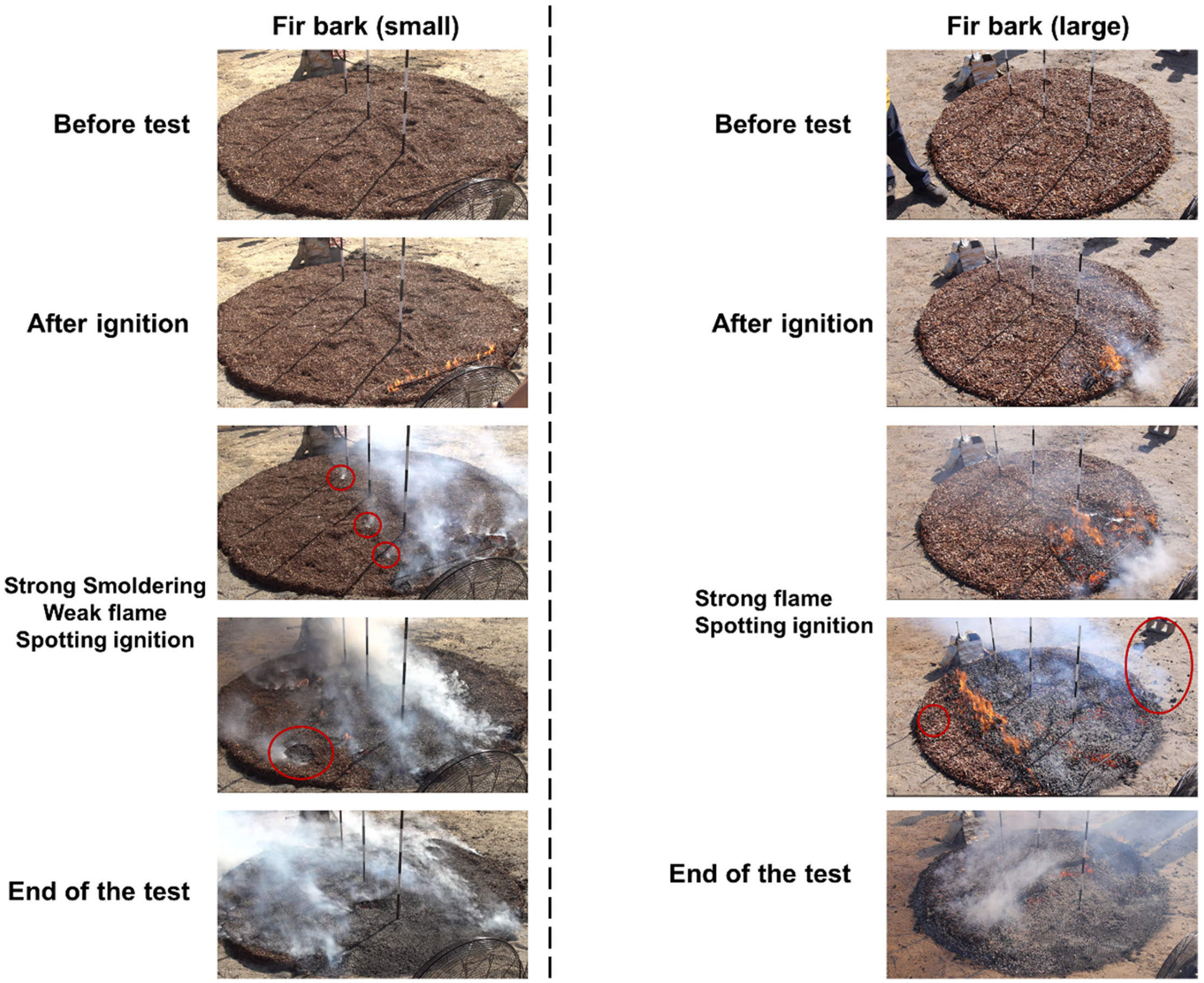

Fig. 10. Progression and key fire behavior phenomena of tests using fir bark with different particle size distributions.

(tree) mulch, Marin Vineyard, and Caltrans, which exhibit rates of 0.18 ± 0.06, 0.29 ± 0.11, and 0.06 ± 0.01 cm/s, respectively.

As discussed under 'Fire behavior', the higher fire spread rate of non-composted mulch can be attributed to the ability of these materials to sustain a flaming fire

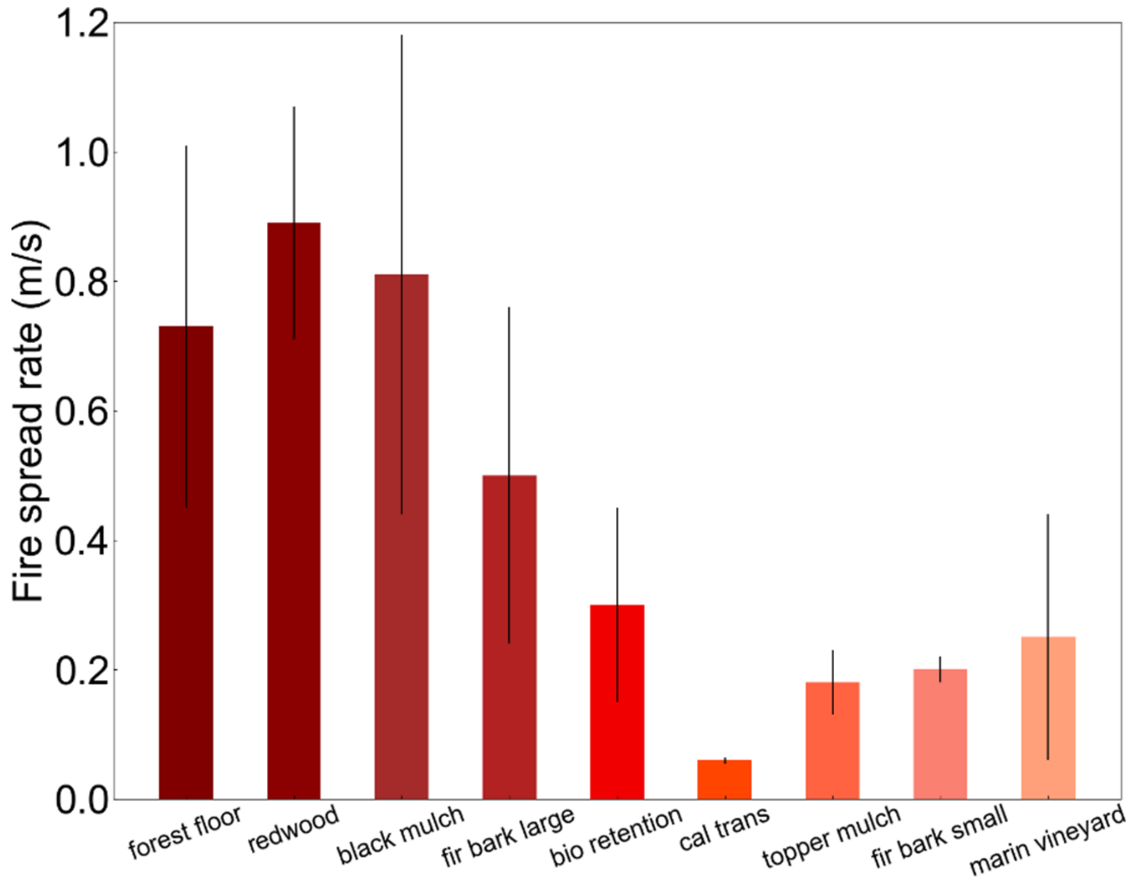

Fig. 11. Fire spread rate calculated based on the moving speed of the fire front. Note: the fire spread rate was calculated as the moving speed of the burning region (including the flame front or smoldering front), and the effect of spotting ignition by moving embers was not considered here. Moreover, the fire spread rate of screened compost was not shown, as the fire only burned locally without spreading within the mulch bed. The error bars represent the standard deviations of the repeated tests.

during combustion. Flaming combustion is typically much faster than smoldering due to higher heating rates that more quickly ignite new material. In contrast, composted mulches primarily undergo smoldering combustion, which leads to a slower rate of fire spread.

Furthermore, particle size distribution and resulting fuelbed structure may influence burning behavior and fire spread rate by affecting fuel packing, permeability, and oxygen transport within the mulch layer. As seen in Fig. 11, fir bark mulch with a smaller particle size primarily supported smoldering combustion, with a fire spread rate of approximately 0.2 cm/s. On the other hand, fir bark mulch with larger particles was able to sustain flaming combustion, with a fire spread rate of approximately 0.5 cm/s. Because these two mulch products originated from the same material but differed primarily in particle size distribution, this comparison provides evidence that particle size and fuelbed structure can substantially influence mulch combustion behavior. Larger particles generally create greater pore spaces and improved ventilation within the fuelbed, facilitating oxygen transport and sustained flaming combustion, whereas finer particles tend to compact more readily and suppress airflow.

In summary, the fire spread rates of mulch products were governed by multiple factors, including whether the mulch was composted or non-composted and the particle size distribution. Non-composted mulches generally exhibited faster fire spread rates due to more sustained flaming combustion, whereas composted mulches tended to burn more slowly, with combustion dominated by smoldering behavior. Particle size further influenced the combustion mode and, consequently, the spread rate: smaller particles, with reduced porosity and limited oxygen availability, were more prone to smoldering combustion, while larger particles, with higher bed permeability and improved oxygen transport, were more conducive to flaming combustion.

Flame height

The flame height refers to the vertical distance from the base of the flame to the highest point of the flame tip. This parameter is critical in fire modeling and fire safety design,

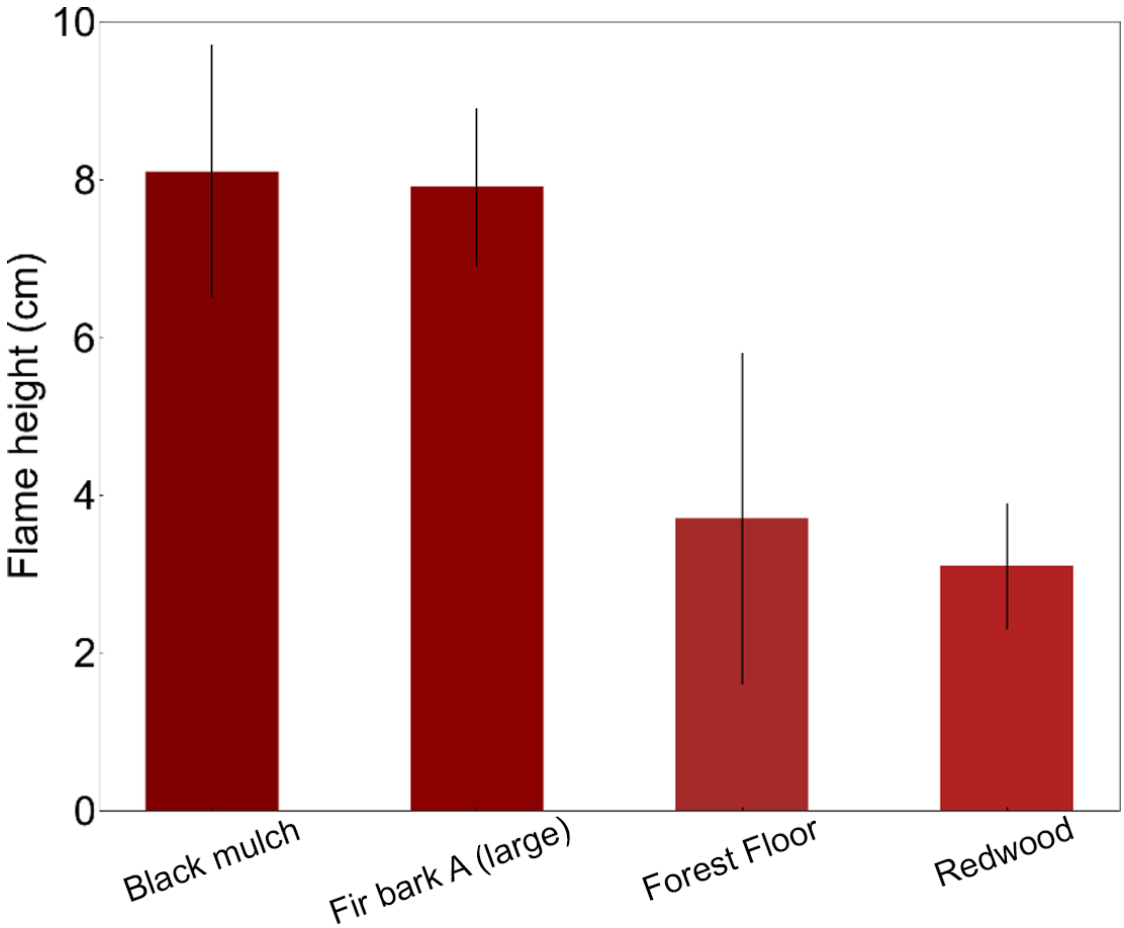

Fig. 12. Flame height of mulch products that can sustain a flame at the center of the test area. Those for which smoldering dominated after ignition were excluded from this analysis. The error bars represent the standard deviations of the repeated tests.

as it can be related to both the intensity and spread of flames, especially in relation to adjacent structures. Given the significance of flame height in quantifying the thermal impact on nearby materials and structures, we utilized Flame Tracker (ver. 1.4.1; Carmignani 2021), a specialized software package designed to identify and measure flames, to quantify this parameter. The process involved calibrating frames of known dimensions within the captured video frames, allowing the software to track changes in pixel intensity over time and identify regions of flame. The maximum height of flames was then extracted and averaged during a period of maximum flame height towards the center of the test region.

Fig. 12 summarizes the flame height measurements for different mulch samples. It is important to note that the time over which frames were measured were selected to represent the moment when the flame front became self-sustaining and continued until no consistent flame remained. Mulch samples that did not sustain a flame at the center of the test area, and those for which smoldering dominated after ignition, were excluded from this analysis. Consequently, the data presented here pertains only to non-composted mulch samples. As shown in Fig. 12, black mulch and fir bark with larger particle sizes exhibited the highest flame heights, approximately 8 cm, indicating that these materials support more vigorous combustion compared to others. In contrast, forest floor mulch and redwood mulch demonstrated lower flame heights, averaging approximately 4 cm, suggesting a less intense burning process.

Heat flux measurements

Fig. 13 presents a comparison of radiation, convection, and total heat fluxes measured 1 foot (~0.30 m) beyond the bed boundary for a range of mulch products. The results reveal a pronounced distinction between non-composted mulches (black mulch, redwood, forest floor, and fir bark) and composted mulches (bioretention, Topper [tree] mulch, Marin Vineyard, Caltrans, and screened compost). The non-composted materials consistently produced the highest total heat fluxes, typically above 7 kW/m^2,

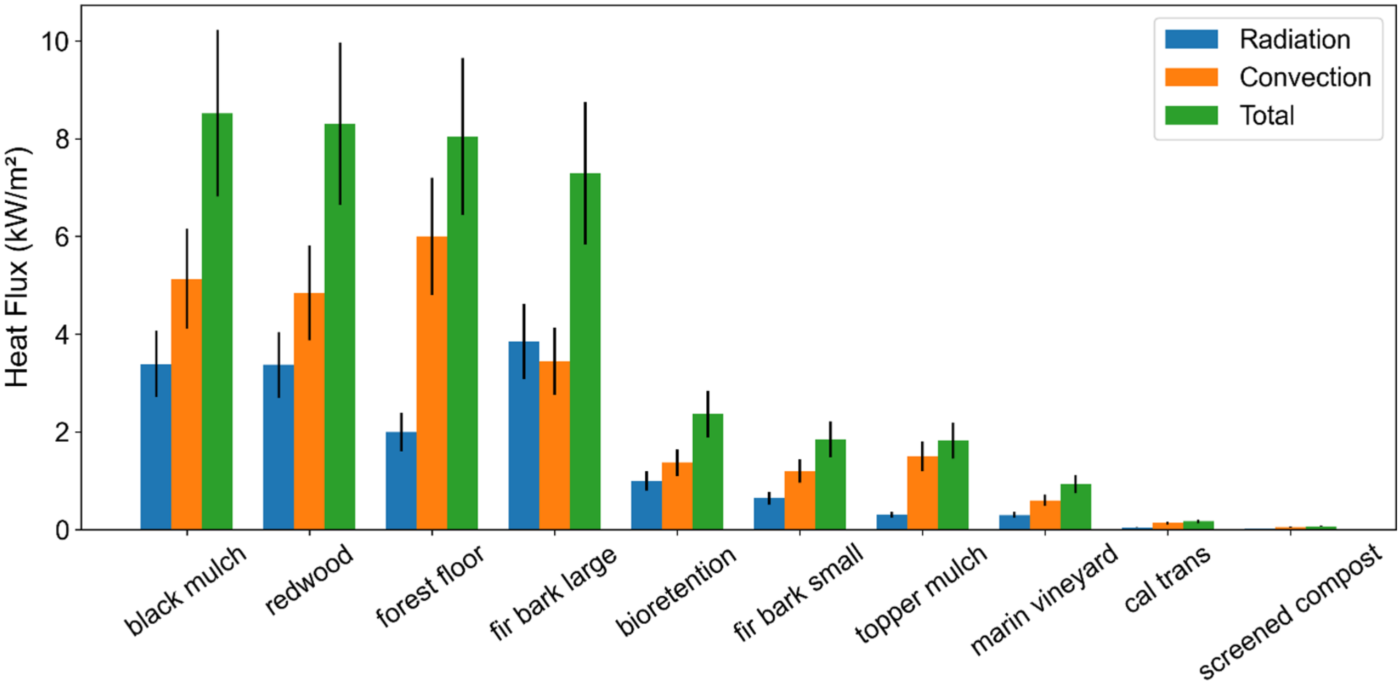

Fig. 13. Comparison of peak radiation, convection, and total heat fluxes from different mulch products, measured at 1 foot (~30 cm) beyond and ~4.6 inches (11.8 cm) above the bed boundary as part of a sensor package. Note: these should be considered conservative estimates of the true fire exposure potential because the actual fluxes experienced near the mulch surface are expected to be substantially higher. The error bars represent the standard deviations of the repeated tests.

reflecting their greater combustible volatile release, lower compaction, and higher combustion intensity. By contrast, composted mulches exhibited much lower heat fluxes, generally below 3 kW/m^2, indicating a substantially reduced exposure potential.

The relative contributions of radiation and convection also varied across products. Black mulch and redwood generated strong radiative and convective components simultaneously, whereas forest floor showed a comparatively greater convective fraction, and fir bark A (large) released nearly balanced amounts of radiant and convective thermal energy. In contrast, composted mulches displayed minimal contributions from both radiation and convection, consistent with their lower flame height and smoldering-dominated combustion.

Although the total heat flux theoretically reflects the combined effects of radiative and convective heat transfer, minor discrepancies between the measured total heat flux and the sum of the independently measured radiative and convective components remain for some mulch products. These differences are attributed to sensor uncertainty, differences in sensor response characteristics, and the transient, spatially nonuniform nature of the outdoor fire environment. Such effects are more pronounced for lower-intensity mulch products, where the measured heat fluxes are relatively small and therefore more sensitive to short-duration fluctuations. Nevertheless, the measurements consistently demonstrate that non-composted mulch products generated substantially greater thermal exposure compared to composted mulches.

The role of particle size is highlighted in the comparison between large and small fir bark. Large fir bark, characterized by coarser particles, produced total heat fluxes exceeding 7 kW/m^2, supported by vigorous radiant and convective release. Small fir bark, composed primarily of fine particles, produced less than 2 kW/m^2. The enhanced combustion observed in the large-particle mulch is likely attributed to its more open and heterogeneous packing structure, which improves intra-bed permeability and facilitates ventilation, thereby supporting sustained flaming. In contrast, finer particles tend to pack more uniformly at the microscale, reducing pore connectivity and airflow pathways, which can restrict oxygen supply and suppress combustion intensity.

It is important to note that the sensors were positioned 1 foot (~0.30 m) beyond the mulch bed at a height of ~4.6 inches (11.8 cm). As a result, the measured values represent attenuated fluxes at the sensor location, and the actual fluxes experienced near the mulch surface are expected to be substantially higher, particularly for high-intensity non-composted products such as black mulch and redwood. Thus, the values reported in Fig. 13 should be considered conservative estimates of the true fire exposure potential associated with different mulch types but still provide a relative measure between mulch samples.

Discussion

Influence of mulch properties on flammability

The differences in flammability between composted and non-composted mulch products can be further interpreted based on their physical and chemical properties summarized in Table 1, including volatile fraction, bulk density, particle size distribution, and elemental composition. In general, the large-scale tests demonstrated that non-composted mulches were more capable of sustaining flaming combustion, exhibited faster fire spread rates, and produced higher heat fluxes compared to composted mulch products. These differences are consistent with observations from previous small-scale ignition and pyrolysis experiments (Lin *et al.* 2024, 2025), which showed that non-composted mulches generated larger quantities of combustible pyrolysis gases during thermal decomposition.

In previous steady pyrolysis experiments using a custom-made linear tube-heater apparatus, the composition and mass flux of gaseous products released from mulch samples were quantified under external irradiation (Lin *et al.* 2025). Methane (CH_4) was identified as the dominant hydrocarbon species emitted from all mulch products during pyrolysis. However, the total mass flux of combustible hydrocarbons varied substantially between mulch types. For example, forest floor mulch produced a hydrocarbon mass flux of approximately 0.6 g/m^2 s, whereas screened compost produced only approximately 0.2 g/m^2 s under similar heating conditions. These larger hydrocarbon release rates from non-composted mulches promote the formation of flammable fuel-air mixtures above the fuelbed, thereby facilitating flaming ignition and sustained flame spread. This behavior is consistent with the present large-scale observations, where non-composted products such as black mulch, forest floor, redwood, and large fir bark sustained vigorous flaming combustion throughout much of the burning process.

Although volatile fraction is commonly associated with fuel flammability, the present results suggest that the total volatile fraction alone is insufficient to explain the observed burning behavior. Some composted mulch products still exhibited relatively high volatile fractions. For example, bioretention mulch had a volatile fraction of 82.8%, comparable to black mulch (86.6%) and redwood (85.8%). However, bioretention mulch did not sustain strong flaming combustion in the large-scale tests and instead primarily burned through smoldering combustion. This observation suggests that the composition and flammability of the evolved gases are more important than the total volatile yield alone. Composting partially decomposes the original lignocellulosic material through microbial activity, altering the chemical structure of the mulch and potentially reducing the production of highly flammable gaseous species during pyrolysis. As a result, even when the overall volatile fraction remains relatively high, the evolved gases may contain a smaller proportion of combustible hydrocarbons capable of sustaining flames. Furthermore, composted mulch products may release larger fractions of non-combustible gases, such as carbon dioxide and water vapor, during thermal decomposition, which dilute the fuel-air mixture and further suppress flaming combustion.

Bulk density also likely contributed to the observed burning behavior. Screened compost exhibited the highest bulk density among all mulch products tested (571 kg/m^3), substantially exceeding that of the non-composted products, which generally ranged between 130 and 253 kg/m^3. The higher bulk density likely reduced pore space and restricted oxygen transport through the fuelbed, suppressing flaming combustion and favoring lower-temperature smoldering processes. In contrast, the lower-density non-composted mulches allowed improved ventilation and oxygen availability within the porous fuelbed, supporting sustained flaming combustion and faster fire spread. A similar effect was observed in the comparison between large and small fir bark products. Despite having nearly identical chemical composition, the larger fir bark particles sustained vigorous flaming combustion and generated higher heat fluxes, whereas the smaller particles primarily smoldered. The smaller particles likely compacted more readily, reducing permeability and limiting airflow within the fuelbed. In addition, larger particles may facilitate the development of localized void spaces and buoyancy-driven flow pathways that enhance oxygen supply to the pyrolysis zone and stabilize flaming combustion.

Elemental composition may have further influenced the combustion behavior. In general, the composted mulch products exhibited slightly lower carbon and hydrogen contents and higher nitrogen contents compared to the non-composted products, reflecting the effects of biological decomposition and mineralization during composting. These compositional changes may reduce the effective heat of combustion and alter the pyrolysis chemistry, contributing to the weaker flaming behavior observed in composted mulches. For example, screened compost exhibited the lowest carbon content (37.8%) and the highest nitrogen content (1.9%) among all products tested, consistent with its inability to sustain flaming combustion under the present experimental conditions. In contrast, non-composted products retained higher fractions of undegraded lignocellulosic material, which likely contributed to greater combustible volatile production and higher heat release during flaming combustion.

Overall, the enhanced flammability of non-composted mulch products appears to result from a combination of greater combustible hydrocarbon release during pyrolysis, lower bulk density and improved ventilation within the fuelbed, and higher combustible organic content. In contrast, composting alters both the physical structure and chemical composition of the mulch, leading to weaker flaming combustion and a transition toward smoldering-dominated fire behavior. The present results therefore highlight that mulch flammability is a multiscale phenomenon governed not by a single property, but by the interaction between pyrolysis chemistry, volatile gas flammability, fuelbed permeability, particle packing, oxygen transport, and heat transfer within the porous mulch layer.

Scale effects on mulch ignition and fire behavior

The objective of both previous small-scale (Lin *et al.* 2024, 2025) and the current large-scale experiments presented was to evaluate the relative ignition and burning behaviors of 10 landscaping mulches and the influence of composting and particle size on performance. Although both scales examined similar parameters, the findings differed due to the scale of the tests and the more complex dynamics observed in the large-scale setup.

The small-scale tests primarily quantified ignition thresholds of various mulch products, including composted and non-composted types (see Table 2). These experiments were designed to investigate the mode of ignition (smoldering versus flaming) and the effect of external factors like firebrand piles, imposed wind, and irradiation. The results indicated that non-composted mulches, such as black mulch and fir bark, were more susceptible to transitioning from smoldering to flaming combustion, while composted mulches exhibited a lower ignition susceptibility. The wind speed also played a crucial role in the ignition process, with higher speeds decreasing the required mass of firebrand piles needed to trigger ignition. These small-scale tests helped identify key factors influencing ignition, particularly how particle size affects the ignition mode and the transition from smoldering to flaming combustion. In contrast, the large-scale experiments offered a more realistic depiction of fire behavior over larger areas, observing how different mulch types reacted under representative fire conditions. The results showed that all non-composted mulches such as black mulch, redwood, and fir bark, were able to sustain flames, whereas composted mulches, such as screened compost, could not support a sustained flame and only exhibited weak smoldering combustion. On the other hand, composted mulches transitioned to smoldering combustion, resulting in slower fire spread. Notably, spotting ignition was also observed during the large-scale experiments, where wind-driven embers ignited downwind fuels, which accelerated the fire spread. This was especially but not exclusively evident in the fir bark product with larger particles, which produced large embers that could travel downwind and ignite new fire points.

Additionally, the large-scale tests included flame height measurements, which indicated that black mulch and fir bark with larger particles exhibited higher flame heights, approximately 8 cm, indicating more vigorous combustion. In contrast, forest floor and redwood mulches showed lower flame heights, averaging approximately 4 cm, reflecting a less intense burning process. These flame height differences were consistent with the faster spread rates of non-composted mulches observed in both small and large-scale tests.

The key differences between the two scales lie in the fire behavior, ignition thresholds, and the role of spotting ignition. While the small-scale tests focused on initial ignition conditions and the transition from smoldering to flaming combustion, the large-scale tests captured sustained fire behavior, including fire spread and ember displacement. Spotting ignition was observed in the large-scale experiments, where embers displaced by the wind ignited new areas of fuel, further accelerating the fire spread. This phenomenon was less pronounced in the small-scale tests. Furthermore, the flame height and fire spread rate measurements from the large-scale tests provided more comprehensive data on how mulch type affects fire dynamics in real-world conditions.

Limitations and perspectives

While the large-scale outdoor experiments conducted in this study provide valuable insights into the ignition and burning behavior of mulch in realistic wildland–urban interface (WUI) conditions, several limitations should be acknowledged. First, the tests were performed under a specific set of environmental conditions in Marin County, including prevailing and imposed winds, ambient temperature, and relative humidity. Although two fans were used to provide a nominally controlled wind field, the outdoor experimental environment occasionally introduced variability in wind conditions due to ambient atmospheric flows. Consequently, wind speed varied modestly during individual experiments, between tests, and spatially across the mulch beds. However, because the imposed wind speeds were relatively low compared to those encountered during severe wildfire events, these fluctuations did not produce substantial changes in the overall burning behavior, ignition mode, or fire spread characteristics observed in the experiments. The primary observable influence of the varying wind conditions was on local flame tilting and smoke plume behavior. Nevertheless, the experiments do not encompass the full range of wind-driven fire dynamics expected under extreme wildfire conditions, where stronger winds could significantly alter flame spread, ember transport, oxygen supply, and fire intensity.

Second, the experiments considered only a limited set of particle size distributions, and weathering periods (e.g. no cycling of rain/drying which may result in changes in

Table 2. Summary of small-scale experiments showing the minimum critical heat flux for ignition by radiation ($q''_{ig,min}$) piloted flaming ignition time (t_{ig}) and peak heat release rate ($pHRR$) at 50 kW/m^2, and the minimum mass of smoldering firebrands ($m_{fb,min}$) required to ignite a sample of mulch $m_{f,b}$ from (Lin *et al.* 2024, 2025).

Test setups	Ignition by cone calorimeter			Ignition by firebrand pile	
Mulch types	$\dot{q}''_{ig,min}$ (kW/m^2)	$t_{ig,50kW/m^2}$ (s)	$pHRR_{50kW/m^2}$ (kW/m^2)	$m_{fb,min}$ (g, up to 0.79 g)	Smoldering-to-flaming? (up to 1.4 m/s or 3.1 mph)
Black mulch	8.9	11.5	215	0.19	Yes
Forest floor	5.4	12.3	218	0.11	Yes
Redwood	8.7	11.7	245	0.19	Yes
Fir bark A (large)	14.8	12.7	204	0.19	Yes
Fir bark B (small)	7.1	12.1	191	0.34	No
Topper (tree) mulch	13.8	13.5	222	0.03	No
Caltrans	11.6	14.3	231	0.03	No
Marin Vineyard	9.3	13.1	191	0.11	No
Bioretention	9.7	14.6	168	0.03	No
Screened compost	22.4	19.7	108	No ignition	No

compaction). Also, no water related degradation (fungal decay) was able to occur). In practice, mulch may accumulate to greater thicknesses, decompose differently under varying environmental exposures, retain litter or other debris, or contain moisture gradients through the thickness of the mulch bed that alter ignition propensity and fire spread. Third, the experiments relied on drip-torch ignition to initiate burning. While this ensured repeatability, actual wildfire ignitions are often caused by firebrands or radiant heating, which may produce different ignition dynamics (Caton *et al.* 2017; Hakes *et al.* 2017). Finally, heat flux measurements were restricted to a distance of 1 foot (~0.30 m) from the mulch bed (Butler *et al.* 2010); closer exposures to flames and embers are likely to produce significantly higher thermal loads, especially for vigorous non-composted mulches.

Despite these limitations, the findings of this work highlight the relative risk of mulch products and directions for future research. Further large-scale studies should expand to different climates, mulch configurations (e.g. size, distribution, thickness), and ignition scenarios, including ember showers and radiant heating representative of real wildfire exposure. The long-term effects of mulch aging, moisture variation, and fungal and insect degradation on flammability warrant systematic investigation, as these processes are likely to influence WUI fire risk. In addition, coupling empirical results with computational fire spread models could improve predictive capability and assist in risk-informed decision making. Ultimately, integrating mulch flammability data into building codes, landscaping guidelines, and community-level fuel management strategies has the potential to enhance fire resilience in WUI communities.

Conclusions

This study represents one of the most comprehensive large-scale experimental investigations of mulch combustibility in an outdoor WUI environment. Results demonstrated that non-composted mulches (black mulch, redwood, forest floor, and fir bark) could sustain vigorous flaming combustion, leading to higher fire spread rates, taller flames, and greater radiant and convective heat fluxes compared to composted mulches. By contrast, composted mulches generally exhibited unstable or self-extinguishing flames and were dominated by smoldering combustion, which significantly slowed but did not stop fire propagation. Particle size was also found to be a decisive factor: large-particle fir bark supported sustained flaming with elevated flame heights and heat fluxes, whereas small-particle fir bark favored smoldering and lower-intensity burning. These findings underscore the importance of both composting and particle size in governing mulch fire behavior.

By directly comparing small-scale ignition thresholds with large-scale fire dynamics, this work demonstrates that laboratory-scale tests capture important ignition mechanisms but do not fully reproduce sustained burning, fire spread, and spotting phenomena observed under outdoor conditions. The results provide critical empirical evidence that can inform fire hazard assessments, landscape design, and defensible space regulations in wildfire-prone regions. In particular, the substantially reduced fire spread potential of composted mulches under the conditions tested suggests that their use may provide a safer alternative to non-composted products in the WUI. However, caution must still be applied adjacent to structures because these composted mulches can support smoldering flame spread that, in the presence of litter or other debris, could transition to flaming. Other construction details, such as proximity of the bottom of the exterior wall to the ground, will also be a factor in evaluating the overall hazard of a noncombustible mulch product. Even with a noncombustible siding material, the underlying wood-based sheathing can still be vulnerable, even to a smoldering material, if the exterior wall is in close proximity to the ground. Overall, the study advances understanding of mulch fire dynamics, bridging laboratory insights with real-world fire scenarios, and provides a foundation for developing science-based guidelines to reduce fire risks to communities at the WUI.

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Data availability. The data that support this study will be shared upon reasonable request to the corresponding author.

Conflicts of interest. The authors declare that they have no conflicts of interest.

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