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Abstract

Field observations show that combustible landscaping features are a common pathway leading fire spread directly to homes during wildland-urban interface (WUI) fires. NIST is studying how these features around a home, including landscape timbers, burn to better understand their levels of hazard and potential roles in spreading WUI fires. A series of field experiments was conducted to examine the effects of landscape timbers, often used as retaining walls or garden borders, on fire spread toward a structure under conditions that may be encountered during a WUI fire. The fire behavior of landscape timbers in multiple configurations was studied under various wind conditions. Sixteen experiments were conducted. Landscape timber types included pressure-treated rounded 7.0 cm x 8.9 cm (2.75 in x 3.5 in) pine timbers, pressure-treated 14.0 cm x 14.0 cm (5.5 in x 5.5 in) pine lumber, and creosote-treated 17.8 cm (7 in) by 22.9 cm (9 in) railroad ties. Configuration variations included the number of timbers vertically stacked, the presence of mulch, orientation, and exposure on one or both sides. A wind machine provided a mean wind speed of nominally 6 m/s (13 mi/h) for most experiments. Timbers were ignited by a propane burner on the ground at the end farthest from a small structure located 1.83 m (6 ft) downwind of the trailing end of the timber. For most experiments, a target mulch bed at the base of the structure evaluated the ability of firebrands produced by the burning landscape timbers to ignite spot fires that could threaten the structure. A final experiment compared burning behavior of a stack of timbers in the open compared to one used as a retaining wall.

The experiments in this study demonstrated that landscape timbers can be sources of spot fire ignitions, can spread fire to nearby structures, and may exhibit deep-seated fires embedded within and between timbers. Fire behavior was classified as high hazard for moderate fire spread rates along timbers, igniting spot fires under all wind conditions, and the propensity of fire to embed in landscape timbers and resist extinguishment efforts.

Spot fire generation was affected by the wind field; the structure created both upward flow (enhanced by buoyancy) and a vortex that deposited firebrands next to the structure. During most but not all experiments, the burning landscape timbers, sometimes with a burning mulch bed, produced firebrands that ignited spot fires in the target mulch bed.

This study of the fire hazard of landscape timbers is part of a series designed to better inform standards and codes regarding placement of landscape features around homes that are at risk of exposure to wildland-urban interface fires.

Keywords

Embers; landscape timbers; retaining walls; firebrands; fire spread; structural ignition; structure vulnerability; wildland urban interface fires; wind-driven fires; WUI fires.

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Acknowledgments

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1. Introduction

This report is the third in a series of NIST (The National Institute of Standards and Technology) experimental studies on fire spread from landscape combustibles to a structure. The studies looked at fire spread from both flames and firebrands. In the first report, we presented a study on fire spread from fences and mulch [1]. In the second report, we presented a study on fire spread from firewood piles [2]. In this report, we describe the hazard to a structure from burning landscape timbers. The experiments were performed outdoors at the Frederick County Public Safety Training Facility at the same location as the previous fence and woodpile studies with a nearly identical experimental setup, instrumentation, and procedure. For the readers' convenience, the sections of this report describing those common aspects are repeated here, with slight adjustments to account for differences between the experimental series.

The trees, grass, brush, and organic debris that make up wildland vegetation are not the only fuels for wildland-urban interface (WUI) fires. Once such a fire reaches a community, its structures and landscape features can add to and may come to dominate the fuels, magnifying the hazard. Combustible elements in a neighborhood may transform from being the targets of flames and firebrands to fire sources themselves that threaten surrounding properties and the people who live there. How and where we build, then, affects the progression of a WUI fire.

NIST has undertaken a long-term project to assess fire hazards in our built environment and develop a mitigation methodology to harden structures against firebrand and flame exposures. This report on landscape timbers builds on a growing body of NIST research studying fire behavior and how the materials, designs, and configurations in a community influence a WUI fire.

1.1. Motivation

The wildland-urban interface refers to areas where dwellings are adjacent to or intermixed with wildland vegetation. A large and growing number of people live in WUI areas in the United States. Residents are attracted to the WUI due to the closeness to natural settings and amenities and to the relative affordability of housing farther from urban centers. The regions where the WUI overlaps with high risk of wildland fires due to fuel, weather, terrain, and sources of ignition are where these wildland fires pose the greatest risk to lives and property. Effective methods are needed in these areas for protecting people, homes, and communities from wildfires.

WUI fires can occur when wildland fires cannot be controlled, often due to extreme wind and fuel conditions, and spread into communities. Such fires have caused significant losses to life and property in the U.S., Canada, and other parts of the world including Australia and Mediterranean Europe. The costs of damage to the built environment associated with wildfires have increased in time; of the 20 most destructive fires in California history, more than half occurred since 2017 [3]. At the top of this list is the Camp Fire of November 2018, which resulted in 85 fatalities and the destruction of over 18 000 structures, including 90 % of the homes in Paradise, CA. The Camp Fire was one of the costliest natural disasters of 2018, with an overall loss of $16.5 billion as estimated by multinational insurance company Munich Re [4]. The second most destructive fire was the Tubbs Fire in Sonoma County in October 2017, which resulted in 22 deaths and over 5 000 destroyed structures. Research is urgently needed to better understand WUI fire-structure interactions and to support changes to building and community designs and codes in order to mitigate the increasing losses from the growing number of WUI fire incidents.

Combustible landscaping elements can act as both potential ignition sites from existing fires (targets) and sources of fire spread themselves. These materials can be ignited by a fire through direct flame contact, radiation, convection, or firebrands. Firebrands, also referred to as embers, are carried by the wind and may ignite combustible materials in a community far downwind of the fire front. Once ignited, landscape combustibles may ignite nearby objects, including homes, through direct flame contact or firebrands. Landscape timbers have been identified as contributors to the spread of WUI fires within communities. Instances of fires spreading to structures from landscape timbers were observed in the Witch Creek Fire [5]. In the case study of the 2011 Amarillo fires [6], it was discussed that first responders reported extinguishing the same railroad ties multiple times due to reignitions demonstrating the propensity of fire to embed within retaining walls and landscape timbers and resist extinguishment efforts. This may consume suppression resources and lead to delayed or prolonged threats to structures long after initial fire exposures.

The protection of people and property in the WUI depends in part on improvements to building and landscape materials, design, and maintenance practices. Efforts to improve community resistance to fire include: WUI building code organizations, such as the International Code Council (ICC), the National Fire Protection Association (NFPA), and Chapter 7A in the California Building Code; and voluntary fire outreach programs, such as Firewise, Fire Adapted Communities, and the Fire Learning Network. Concepts like defensible space and the home ignition zone educate the public on how to protect their homes. Recently, a fire hazard mitigation methodology[1] (HMM) was developed based on the relationships among fuel layout, fire hazard, and structure hardening [7].

For maximum effectiveness, these efforts require science-based data and guidance. Increased understanding of the vulnerabilities of structures in WUI communities and the potential pathways for flames and firebrands will help to enhance life safety and improve community resilience to these fires. The hazard may be reduced through improvements in materials, building designs, and configurations. Landscape timbers present a challenge because non-combustible alternatives are not commonly available or as economical. In order to determine whether landscape timbers should be used on properties in at-risk areas, the relative hazard they represent needs to be understood.

The goal of this research was to improve our understanding of the mechanisms by which landscape timbers can transport fire to a home, with a focus on firebrand ignition of near-building combustibles. Better understanding of the role of these features as conduits of fire spread to structures and identification of particularly hazardous configurations promote efforts

[1] The Hazard Mitigation Methodology (HMM) [6] has been developed in a collaboration among NIST, The California Department of Forestry and Fire Protection (CAL FIRE), and the Insurance Institute for Business & Home Safety (IBHS).

to protect against ignition and fire spread. Helping fire departments to identify very high hazard situations will enhance first responder safety and effectiveness. The results of this work will be used to influence codes, standards, and best practices and to provide guidance to homeowners, community designers, and first responders.

1.2. Background

WUI fires ignite the exteriors of structures through flame radiation and convection, direct flame impingement, and firebrands (also called embers). In contrast to the large body of knowledge on ignition and fire growth within buildings, reflecting decades of fire research, the complexities of the interactions between the built environment and exterior fire exposure are in the early stages of exploration. Our understanding of WUI fire behavior is confounded by the large number of potential fire and firebrand exposure scenarios (with added complexities of local topography such as slope and local weather such as wind and humidity), the wide variety of WUI fuels (vegetative and structural), and the extensive assortment of exterior construction materials and assemblies (with responses affected by particular designs and weathering). The research presented in this report joins earlier efforts to better understand structure vulnerabilities to fires from nearby landscape combustibles.

1.2.1. Structure Vulnerabilities

Fire may ignite a structure through numerous pathways. At close range, exposed combustible materials may ignite through radiation/convection or direct flame contact. Ignitions may also occur through firebrands. These burning particles break off from a larger object in a fire and are blown or lofted to a new location, where they can ignite spot fires. Firebrands may ignite susceptible parts of the building exterior and may penetrate into interior spaces through vulnerable openings in the building envelope. An object ignited by flames or firebrands may itself become a fire source of additional firebrands and flame radiation exposures to surrounding fuels (targets).

1.2.2. Landscape Feature Fire Studies

Similar to fences, landscape timbers and retaining walls usually have a linear character and can act as connections of burning material to or near a structure. Figure 1 shows three photographs of typical landscape timber usage as a flower bed or sidewalk border, for a raised flower bed, or as a retaining wall. It is common, especially where WUI fires are not a concern, for landscape timbers to be located near or against residences or auxiliary structures or at the edge of parcels where they may be close to structures on an adjoining lot. In these cases, exposure of nearby combustibles to landscape timber flames could be an issue. Figure 2 shows a photograph of a large burned retaining wall adjacent to the remains of home after a WUI fire event. Figure 3 is a close-up view of a section of the wall which shows that much of the wood was consumed.

Landscape timbers also share the firebrand generation aspect of other landscape fuels. The recent NIST study on fences [1] found that: 1. a combustible ground cover such as mulch can generate many firebrands that ignite downwind spot fires and 2. when combined with fences, firebrand production was enhanced. Also, particularly hazardous materials and configurations were described. The report [1] listed prior studies of fences and mulch.

Fig. 1 Examples of landscape timber usage: flower bed border (upper left), raised bed (upper right), and retaining wall (bottom).

The recent NIST study on firewood piles [2] found that burning woodpiles: 1. generate copious amounts of firebrands, igniting spot fires in a bed of combustible material within 3 min or less; 2. can bring spot fire flames to a structure adjoining the bed in less than 5 min; 3. can produce wind-blown fire plumes, extending 1 m (3.3 m) steadily to 2 m (6.6 ft) intermittently, that could ignite nearby combustibles; and 4. may collapse, spreading and changing the hazard.

The prior studies showed how fire spreads along these landscape features and provided insight into how firebrands are generated and ignite downwind spot fires. These are also the focuses of the study on landscape timbers described in this report.

1.3. Approach

NIST staff conducted a series of field experiments on the fire spread behavior of ignited landscape timbers to examine the spread of fire directed toward a structure along landscape timbers in the presence of wind. The objectives of the experiments were to observe and analyze the ability of firebrands generated by the burning timbers to ignite spot fires at the base of the structure and to observe any fire behaviors that are particular to landscape timbers. Some experiments included a mulch bed burning in combination with the timbers to determine if this common configuration enhanced fire spread and spot fire ignition.

Fig. 2 A photograph of a burned retaining wall behind the remnants of a home destroyed during the Tubbs Fire in California (2017).

Fig. 3 A photograph with a close-up view of a section of burned retaining wall after the Tubbs Fire.

The authors used a portable, airboat-style wind machine fan to direct a wind field with a prescribed speed along the landscape timbers, usually in the direction of a small shed. An individual landscape timber or stack of timbers was placed at a prescribed location between the fan and the shed (if present). For some experiments, the landscape timbers were surrounded by a bed of mulch which could also burn. The wood was ignited with a propane burner at the end near the fan, and the growth of the fire and generation of firebrands were observed. When present, the small shed was used as a target structure for firebrands, and a target mulch bed was placed along the base of the shed wall to observe spot fire ignitions from firebrands. Three types of landscape timbers in different configurations were used in the experiments.

Realistic, yet relatively small, sets of landscape timbers were used. The findings provide context for the hazard from larger assemblies but are not necessarily to be extrapolated linearly. Additional limitations of the study are listed in Section 4.3.

1.4. Objectives

The overall goal of the work described in this report is to assess the severity of the fire hazard that landscape timbers pose to structures. This was accomplished by studying the mechanism of fire spread in the presence of wind as the fire grew, became embedded in the timbers, and jumped via firebrands from the landscape timbers to combustible materials at the base of the shed. The main objectives of the experiments were:

- To observe the burning behavior of wind-driven landscape timber fires, including fire spread rate and fire embedding within and between timbers;
- To determine whether landscape timbers produce firebrands capable of igniting downwind combustibles and posing an ignition danger to a nearby structure;
- To determine the impact of wind speed, timber type, stack height, stack orientation, the presence of mulch, and use as a retaining wall on the generation of firebrand-ignited spot fires that threaten a structure.

It is anticipated that this work will contribute technical knowledge that will improve guidance for best practices for home landscape features and to support efforts to address the WUI fire problem by hardening structures and creating defensible space. A device is being developed at NIST to provide quantitative data on firebrand flux and size which will allow more detailed analysis of the firebrands produced by future testing of landscape timbers as well as fences, mulch, and firewood which have been previously studied regarding fire spread.

2. Experimental Design

To investigate the spread of fire through direct flame impingement or firebrand spotting, the authors performed a series of outdoor experiments on landscape timbers erected in front of a structure (in most cases) and within a generated wind field. Figure 4 shows a schematic of the typical experimental setup. A wind machine, consisting of a gasoline engine turning a 2.11 m (83 in) diameter propeller mounted on a trailer, was directed toward a small structure. A flow straightener was employed to remove large-scale swirl from the supplied wind and to direct the wind downward slightly toward the ground. An individual landscape timber or stack of timbers was arranged at a prescribed location between the structure (or where the structure would be if present) and the wind machine. The timber was usually oriented perpendicular to the wall of the structure, with an angular orientation used for a couple of experiments. For some experiments, the landscape timbers were surrounded by a bed of shredded hardwood mulch. The separation distance from the landscape timber to the wall of the structure (if present) was fixed at 1.83 m (6 ft); therefore, the end of the timber furthest from the wind machine was located 8.84 m (29 ft) from the center of the wind machine propeller hub. This differs from the previous studies conducted on fire spread [1] [2] which examined a range of separation distances from the target shed. To study the potential for firebrands to ignite the structure, a target pan of mixed hardwood mulch was positioned at the base of the structure wall. This mulch bed served as a surrogate for any combustible material next to a structure.

The landscape timbers were ignited with a propane burner to simulate prior ignition via either one or more firebrands or a nearby combustible item that in turn provided flaming exposure to the timber. Wind was directed along the landscape timbers. Three wind speeds were used in the study, with nominal values of 6 m/s (13 mi/h) for low, 10 m/s (22 mi/h) for medium, and 14 m/s (31 mi/h) for high wind speed levels. Most of the experiments were conducted at the low wind speed. The fire spread behaviors of multiple landscape timber types, stack heights, and configurations were investigated. The following sections detail the experimental setup, equipment, measurements, conditions, and the parameters explored.

2.1. Research Location and Site Description

The experiments were conducted in Frederick, MD at the Frederick County Public Safety Training Facility. A large, nearly flat asphalt and concrete area near a water-supply pond was utilized. The pond and an adjacent wall provided a non-combustible background downwind of the firebrand-generating experiments. Water for extinguishment was provided through a nearby hydrant and a diesel pump, which provided a high-pressure source of pond water.

An aerial view of the site is shown in Fig. 5, marked with locations of the target shed, equipment/conditioning building, and wind machine. For the usual configuration, as shown, the wind flow was applied from the SSW at an angle of 200° ± 1° measured clockwise from North.

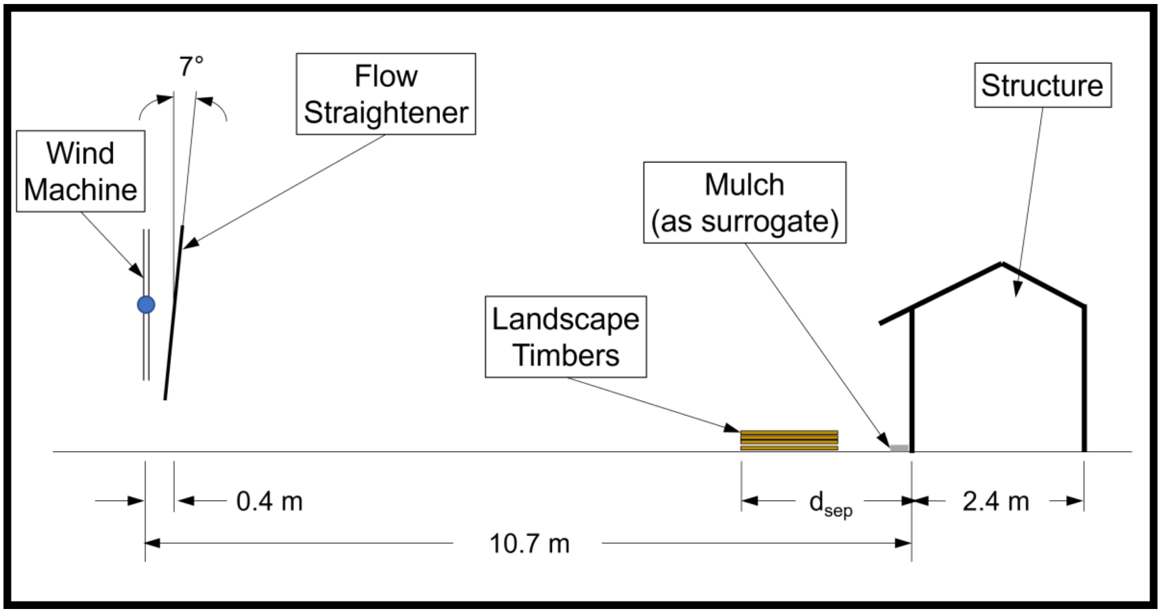

Fig. 4. Major components of the experiment (not to scale).

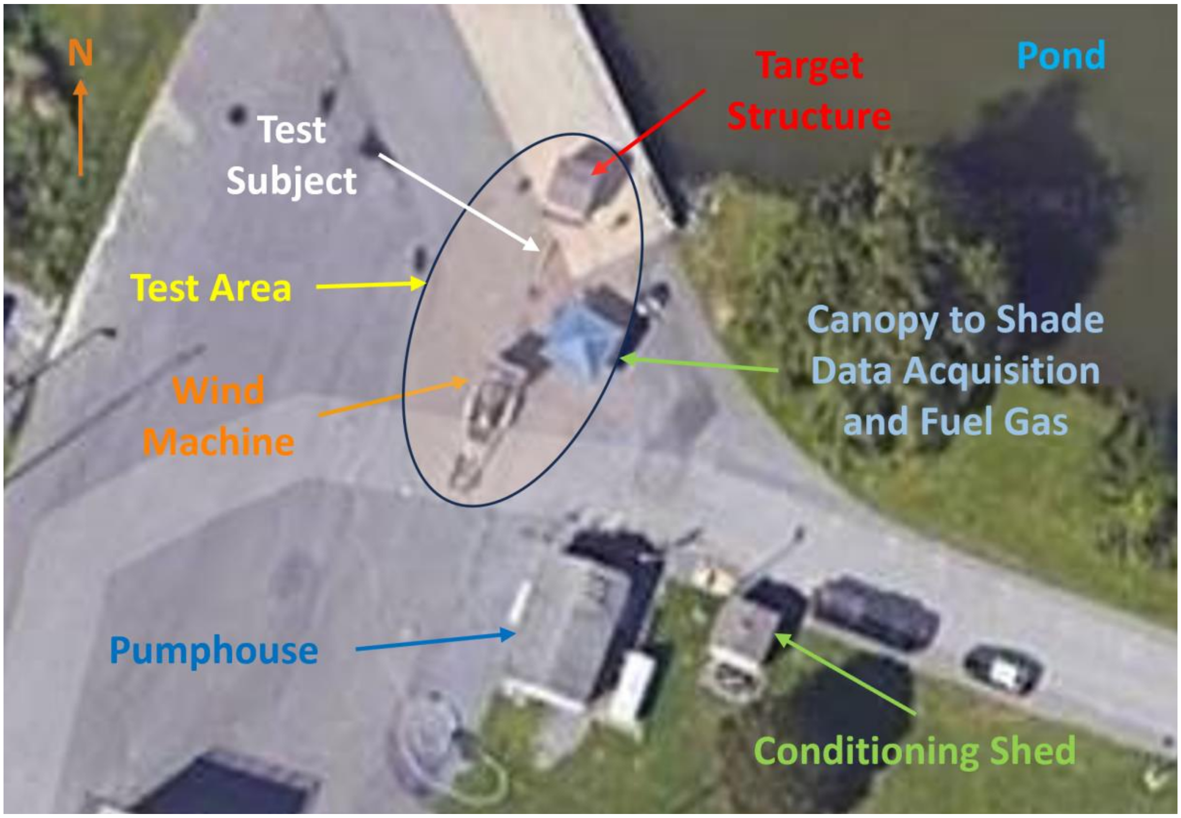

Fig. 5. Aerial view of site used for experiments. Google Earth image with NIST overlay.

2.2. Wind Field Generation

2.2.1. Wind Machine

The wind machine used to impose a wind field on the target structure, shown in the foreground of Fig. 6, was assembled and mounted on a trailer by American Airboat. The power was provided by a 6.0 L displacement, 450 HP rated marine engine with multi-port fuel injection. The wind machine utilized Whirlwind Propellers model AB300ex-WT79, which had three quiet-design, graphite composite blades with a width of 33 cm (13 in) and a sweep diameter of 2.11 m (83 in). The wind machine incorporated a high-performance positive drive belt with 2.3:1 reduction. A manual “cruise control” mechanism was designed and added to the single lever binnacle-style throttle control in order to allow maintenance of selected engine speeds, which were monitored with a built-in tachometer.

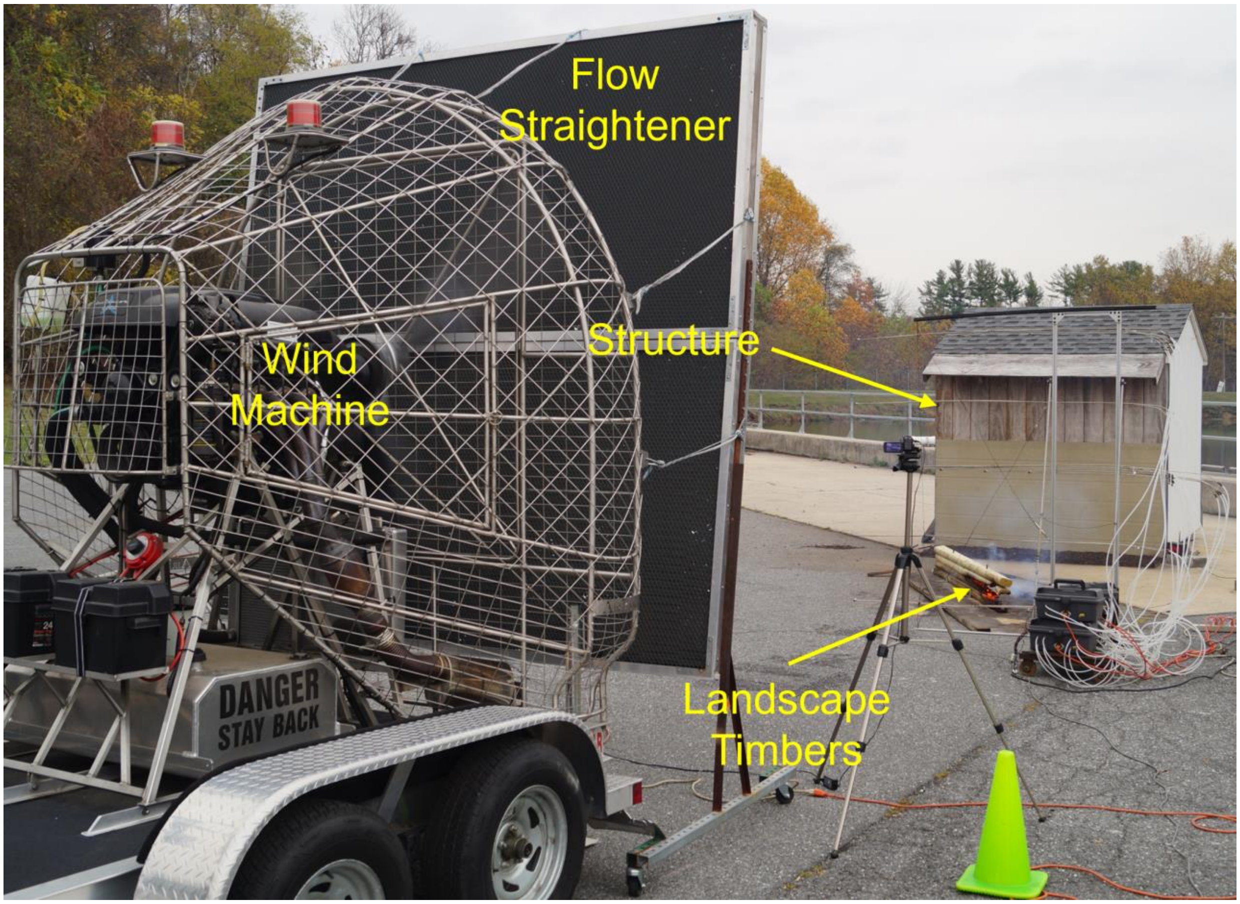

Fig. 6. Photograph of test site showing the wind machine, flow straightener, stack of landscape timbers (angled orientation), and target shed in an experiment.

2.2.2. Flow Straightener

A flow straightener was used to remove large-scale swirl from the supplied wind and adjust the wind direction. The flow straightener consisted of two framed sections of aluminum honeycomb with cells 19 mm (3/4 in) across and 11 cm (4.4 in) thick. The two framed sections, each measuring 1.2 m × 2.4 m (4 ft × 8 ft), were stacked as shown in Fig. 6, with the front plane of the flow straightener positioned 45 cm (18 in) in front of the wind machine fan at the height of the fan center. Since the lowest sweep extent of the wind machine propellers was 1 m above the ground, the column of air moved horizontally by the wind machine by itself would not begin to be felt at the ground for a distance of several meters. To enable the generated wind field to reach the windward end of landscape timbers being tested with substantial velocity, the flow straightener was angled downward by approximately 7°. Measurements of the resulting wind field are discussed in Section 2.6.1 and Appendix B.2.

2.3. Target Shed and Mulch Bed

A target shed and target mulch bed were used as realistic combustible entities with potential to be ignited by flames or firebrands from burning landscape timbers and mulch.

2.3.1. Target Shed

A target shed was used for 12 of the 16 experiments. A mulch bed at the base of the shed served as a surrogate for fine combustible materials (such as leaves or pine needles in addition to mulch) that could ignite, potentially resulting in fire spread to the shed wall. Four experiments that were focused only on fire spread along the timbers were performed without a shed.

A shed with a square footprint (side length 2.43 m [8 ft]) and a height of 2.43 m (8 ft) along the front and rear faces is visible in the background of Fig. 6. The shed was positioned 10.67 m (35 ft) away from the plane of the wind machine propellers. As shown in Fig. 7, an artificial eave was added to the shed on the windward side, extending 45 cm (18 in) outward at the same 30° angle as the roofline. The eave was constructed from standard pressure treated pine two-by-fours[2] and 1.5 cm (0.59 in) thick T1-11 weather-resistant southern yellow pine plywood panel siding.

A false wall was attached to the shed on the windward side to allow replacement of burned wall layers without damaging the original shed wall. The design of the false wall included layers (starting from the inside) of 1.6 cm (5/8 in) gypsum board, standard pressure treated pine two-by-fours (the same type used for the eave), 1.6 cm (5/8 in) gypsum board, and 1.5 cm (0.59 in) thick southern yellow pine plywood panel siding. A JamesHardie™ fiber cement siding panel was added to the bottom of the false wall, as shown in Fig. 7, as a non-combustible layer that prevented the false wall from igniting in these tests and requiring replacement. The plywood panel siding and fiber cement siding were each 1.22 m (4 ft) tall by 2.44 m (8 ft) wide, with thicknesses of 1.5 cm (0.59 in) and 6.4 mm (¼ in), respectively.

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[2] The term "2×4" or "two-by-four" is used to refer to dimensional lumber, also known as framing lumber. The cross-sections of lumber are referred to by their nominal size, in this case 2 in by 4 in, but the actual thickness and width (the "dressed" size) after cutting and either surfacing or planing are 3.8 cm by 8.9 cm (1 ½ in by 3 ½ in) [15]. Similarly, 4×4s measure 8.9 cm by 8.9 cm (3 ½ in by 3 ½ in), and 1×6s measure 1.9 cm by 14.0 cm (¾ in by 5 ½ in).

The false wall and siding layer added approximately 15 cm to the shed depth, for a final shed footprint of 2.43 m wide by 2.58 m deep. The vertical gray strip appearing in Fig. 7 is a metal corner bead protecting the edge of the shed.

Fig. 7. Target shed configuration.

2.3.2. Target Mulch Bed

To evaluate whether the landscape timbers being tested were capable of generating firebrands that could threaten a structure through spot fires, the experiments included a target bed of shredded hardwood mulch placed along the base of the shed wall, as shown in Fig. 8. The target mulch bed was 0.46 m (18 in) wide and 2.44 m (8 ft) long. Two steel pans, each 1.37 m (4.5 ft) long, were overlapped in the middle to create the 2.44 m total length. The pans had 2.5 cm (1 in) walls on the far ends and on the back edge that abutted the shed wall.

The target mulch bed served as a surrogate for any combustible material next to a structure. Because of its rough texture, any firebrands landing on this surface tended to stay in place. Shredded hardwood mulch, shown in Fig. 9, was selected as a conservative worst-case for combustibles near the structure: low moisture, consisting of easily ignited small pieces, and comprised of innumerable crevices in which firebrands could lodge.

The mulch bed was prepared by filling the pans with an even layer of mulch and compressing the mulch by foot. The target mulch bed was 2.5 cm thick, with the first 3 cm of the leading edge slightly tapered down to about 1.5 cm thick to decrease the severity of the abrupt change in height from the ground and to reduce the number of sliding firebrands that were caught at the front edge of the bed.

Fig. 8. Target mulch bed and digital timer.

Fig. 9. A photograph of the shredded hardwood mulch used in the target mulch bed.

The mulch used in these experiments was dried to 6.5 % ± 1 % moisture content. Three alternative drying processes were utilized during the study: natural heating and drying in the sun on an outdoor raised mesh platform (slow, inconsistent, and labor-intensive), mesh bags placed on wire shelving in a wood-drying kiln (a much faster and consistent method described in 2.4.1), and thin layers placed in an indoor space conditioned to 30 % relative humidity (RH) (slow but consistent). A moisture content of 6.5 % was selected because it is on the order of values seen in wood in summertime in the southwestern U.S. [8] – a low value, yet more realistic than the far lower moisture content that could have been achieved through oven-drying.

Mulch moisture content was measured with an Arizona Instruments Computrac MAX 1000 moisture analyzer (see Fig. 10). After drying, the mulch was placed in plastic bins that could hold between 56.6 L (2 ft^3) and 113.3 L (4 ft^3) for storage and transport. The bins were stored either in the conditioned (30 % RH) indoor space or in sealed bins in a building at the test site. The dehumidifying equipment at the test site was unable to reduce the water vapor content below 35 % RH; however, with sealed bins, large amounts of mulch, and a small moisture gradient, the moisture content was not expected to change significantly when moved from 30 % to 35 % relative humidity conditions. A chart of equilibrium moisture content (EMC) of wood as a function of relative humidity and temperature shows that EMC ranges from 5.6 % to 6.3 % at 30 % RH and 6.3 % to 7.1 % at 35 % RH, for temperatures from 43.3 °C to -1.1 °C (110 °F to 30 °F) [8, 9]. Therefore, a moisture content estimate of 6.5 % ± 1 % encompasses the sets of conditions at both sites, as well as the effects of variations in initial drying.

Fig. 10. Moisture analyzer used for measuring moisture content of mulch.

2.4. Types of Landscape Timbers

Three types of landscape timbers were tested to determine if there were any differences in the hazard produced via fire spread or spot fire ignition in a target mulch bed. The first timber type is referred to as "thin" and was made of pressure treated-pine, 2.44 m (8 ft) long with a rounded cross section nominally 7.6 cm (3 in) by 10.2 cm (4 in) but really 7.0 cm (2.75 in) by 8.9 cm (3.5 in). The second timber type is dimensional lumber commonly referred to as a "6×6" and was made of pressure-treated pine, 2.44 m (8 ft) long with a square cross section 14.0 cm (5.5 in) on a side. The third landscape timber is referred to as "RR tie" and was a creosote-treated grade 2 railroad tie of unknown wood type, 2.59 m (8.5 ft) long with a cross section of 17.8 cm (7 in) by 22.9 cm (9 in). The three types are shown in Fig. 11.

Fig. 11 Side view (top) and end view (bottom) photographs of the three types of landscape timbers tested: "thin" (left), "6×6" (center), and "RR tie" (right).

2.4.1. Wood Conditioning

The landscape timbers were purchased at local lumber outlets and were not stored outdoors while in NIST possession. Once obtained, they were stored in a space conditioned to 30 % relative humidity, which drove the wood moisture content to approximately 6.5 %. Usually, timbers were transported from the storage space on the day they were to be used for experiments, but on occasion they were transported within a few days of experiments and stored in a shed kept at 35 % relative humidity. For the short duration and small humidity gradient, the moisture content was not expected to change significantly before testing.

2.5. Ignition Source

The test subject was ignited by a propane burner applied near the end closest to the wind machine. The burner was a customized model that consisted of eight Venturi-style brass torch heads (Bernzomatic brand Pencil Flame model), arranged with four torch heads on each side of the test object. Two torches of each set pointed 45° upward toward the landscape timbers and the other two pointed 45° downward toward the mulch, as can be seen in the overhead view in Fig. 12. The torches were wrapped with Kaowool ceramic fiber blanket and then covered with aluminum foil as shown in Fig. 13 for protection from flames and radiation after ignition of the fence and/or mulch.

Fig. 12. Propane burner for igniting fence and/or mulch, with torches exposed.

2.6. Measurements

2.6.1. Wind Speed Profiles

The experiments were performed under imposed wind speeds from 6 m/s to 14 m/s (13 mi/h to 31 mi/h) perpendicular to and centered on the target shed wall (when present). In order to measure the wind velocity field, an array of thirteen bidirectional probes was placed 1.22 m (4 ft) upwind of the end of the landscape timbers closest to the wind machine. This location was selected to capture the wind field near the timbers that are the focus of the experiment without influencing the upwind measurement. Bidirectional pressure probes measure the difference between the total pressure on the windward side of the probe and the static pressure on the leeward side. The difference is the dynamic pressure caused by the wind, which can be combined with temperature and a probe factor to calculate the wind speed [10]. The leads of the probes were connected to Setra Model 264 bidirectional pressure transducers, which have a pressure range of ±373.6 Pa. Each transducer produced a voltage output from 0 V to 5 V, with 2.5 V output indicating zero pressure differential. Combining the pressure measurement with ambient temperature gave a corresponding velocity range of about 23 m/s (52 mi/h). The transducer calibrations were checked periodically with a pressure calibration system, and their sensitivities were found not to drift significantly. Voltage outputs measured during daily pneumatic zeroing (which will be described in Section 2.8.2) were used to account for any voltage offsets.

Fig. 13. The propane burner protected by a Kaowool blanket and aluminum foil, igniting a set of four thin rounded pine timbers arranged vertically in a mulch bed.

A photograph of the bidirectional probe array in front of a burning set of landscape timbers is shown in Fig. 14, and the diagram in Fig. 15 indicates the locations of probes. The array consisted of five probes arranged vertically on the centerline of the experiment at heights of 0.30 m (1 ft), 0.76 m (2.5 ft), 1.22 m (4 ft), 1.68 m (5.5 ft) and 2.13 m (7 ft) measured from the ground; two sets of two probes each extending out from the centerline in 0.61 m (2 ft) intervals at both the lowest (0.30 m) and highest (2.13 m) positions; and an additional four probes extending out from the centerline in 0.30 m (1 ft) intervals at the middle (1.22 m) position. This allowed for collecting velocity data for a vertical velocity profile at the centerline and a horizontal velocity profile at the center height, and added several additional, more sparsely located, velocity measurements to provide a more complete picture of the velocity field generated by the wind machine.

Ambient temperature was required along with the differential probe pressures to calculate the wind speed. Temperature was measured with a type K thermocouple bead made from 24 AWG wire (0.51 mm diameter). The temperature measurement location was about 2.5 m away from the probe array and shielded from thermal radiation from either the fire or sun.

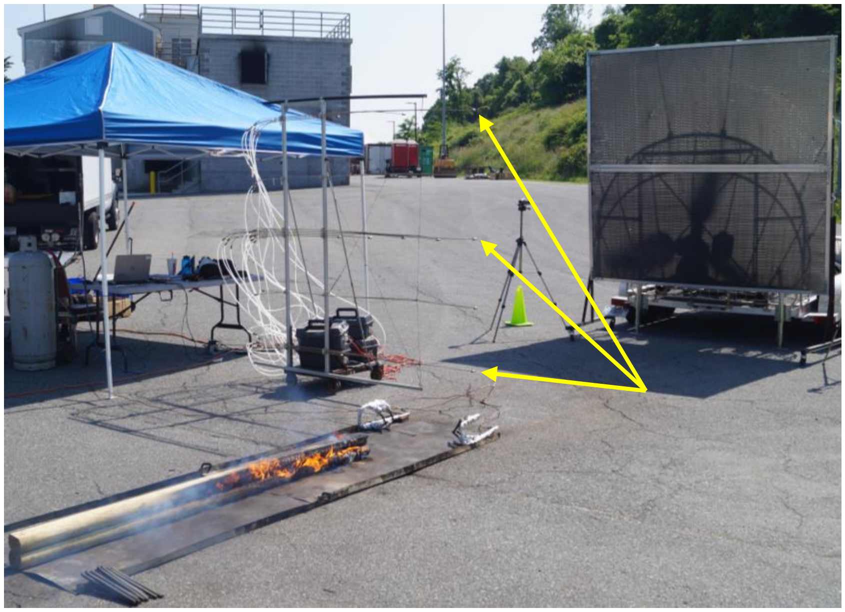

Fig. 14. Bidirectional probe array located between flow straightener and landscape timbers.

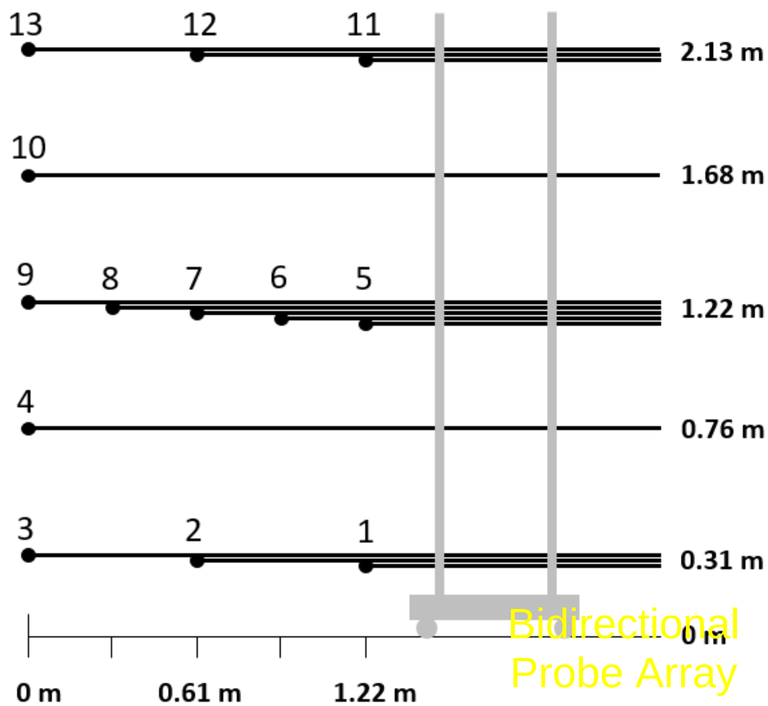

Fig. 15. Diagram of the bidirectional probe array used to measure the velocity field.

The wind profile measured by the bidirectional probe array depends primarily on the wind speed and the distance from the wind machine, with a contribution from the component of ambient winds in the direction measured by the probes. Because the probe array is 1.22 m (4 ft) upwind from the windward side of the landscape timbers and at least 2.74 m (9 ft) upwind from the shed, the effects of these objects on the measured wind field are minimal. For a given experiment, the average of the velocities of the lower four probes along the centerline was used to state the average wind velocity. The rationale for this can be found in the report for the fence and mulch study [1].

2.6.2. Ambient Wind Speed and Direction

The ambient wind speed and direction were measured by an anemometer mounted on a 3.7 m (12 ft) pole about 7.9 m (26 ft) south-southeast of the wind machine propellers and 17.7 m (58 ft) south-southwest of the target shed. The instrument was a Young model 86000 Ultrasonic Anemometer with 5 V output and 0.25 s response time for both wind speed and wind direction. Wind speed was measured with 0.01 m/s resolution, and accuracy was the higher of ± 2 % and ± 0.1 m/s as stated by the manufacturer. The wind direction was measured with 0.1° resolution and ± 2° accuracy. Wind direction accuracy was degraded to about ± 5° due to the estimation of true north during installation and slight positional drift due to high winds which was periodically corrected. The ambient wind measurement provided an approximate wind environment near but not exactly at the location of the experiments, so some focused wind gusts may have been located at the experiment and not the anemometer or vice versa.

2.7. Data Acquisition

2.7.1. Wind and Temperature Data

A data acquisition system was required to measure 16 channels of measurements from the bidirectional probe array located in front of the landscape timbers, an ambient temperature thermocouple, and the local wind speed and direction from the sonic anemometer. Voltage and thermocouple data from the sensors were collected using two National Instruments input modules, NI-9205 and NI-9213, respectively inserted in a National Instruments cDAQ-9174 CompactDAQ USB 4-slot chassis. The data were collected at 10 Hz and averaged over every second for each channel. The program saved the averages and standard deviations of the samples from each channel to the output file, which was stored on a laptop computer and later uploaded to a permanent data storage repository. The LabVIEW program used to collect the data was also used to monitor data quality and spot check for sensor malfunctions.

2.7.2. Digital Video and Photographic Records

A minimum of four high-definition video cameras, Sony model HDR CX-350, were placed around the assembly of landscape timbers and target mulch bed to capture the fire and spotting behavior. Two cameras located on opposite sides of the landscape timbers (pointing perpendicular to the wind direction) included the timbers, shed wall (when present), and target mulch pan in their fields of view. These cameras captured fire spread and spot fire ignition data. An additional two cameras were located upwind of the timbers next to the wind machine flow straightener, including the timbers and, when present, the shed and target mulch pan in their views. For some experiments, a fifth camera was placed on the left side of the experiment near the target mulch bed to more closely record spot fire ignitions. Fig. 16 is a top view schematic of the experimental setup showing the relative positions of the video cameras.

To track experiment time, a DC-Digital timer, model DC-25UT, was placed in view of two or three of the video cameras. The timer, visible in Fig. 7 and Fig. 8, was started nearly simultaneously (within a few seconds) with burner ignition. This allowed the video records of the left view and one or two of the front views of the test setup to also record the timer and thus assist with synchronization of the remaining video camera(s), the two stopwatches used, and the wind data, which was referenced to computer time.

Digital still photographs were taken throughout the testing period and afterward. The digital still camera used was Sony model SLT-A58. The handheld camera was used periodically to capture close-up video of interesting phenomena.

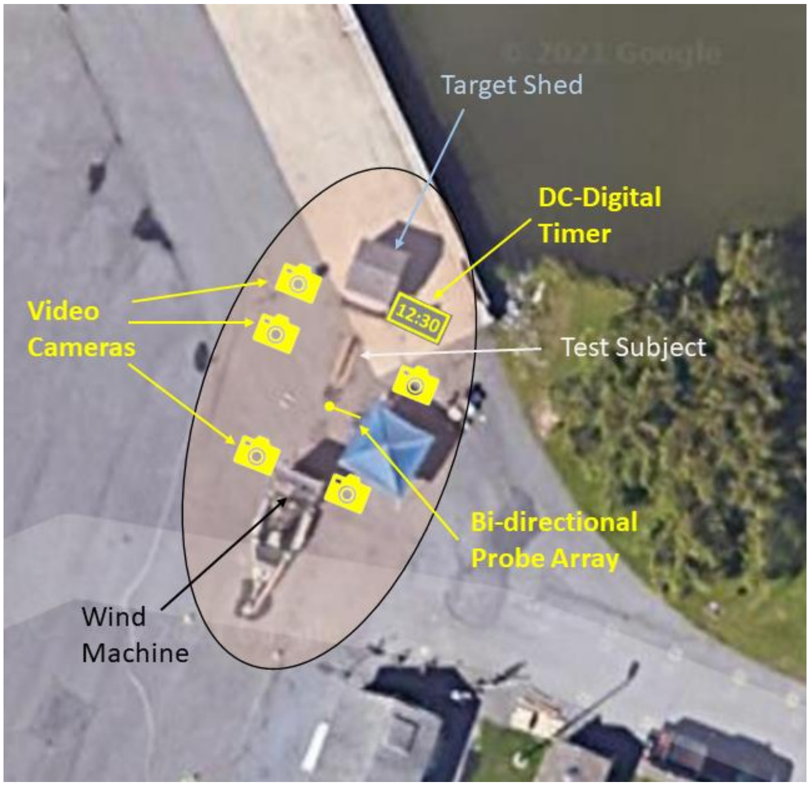

Fig. 16. Top view schematic of experimental setup showing placements of video cameras, timer, and bidirectional probe array. Google Earth image with NIST overlay.

2.8. Experimental Procedures

2.8.1. Weather Conditions

The ambient wind speed was required to be less than 33 % of the nominal applied wind speed in order to carry out the experiment. If the ambient wind direction was forecast to be close to perpendicular to the direction of the generated wind, then ambient winds needed to be less than 25 % of the generated wind (see Section 2.11). Under these conditions, the impact of the ambient winds on the wind field generated by the wind machine fan was sufficiently low to not significantly change the timbers' fire spread behavior. Winds from the North and Northwest were also avoided as they caused smoke and firebrands to overspread the experiment control area.

Testing was usually not scheduled when rain was likely during a substantial part of the morning or afternoon. Excessively hot or cold weather conditions also precluded testing. Generally, experiments were not scheduled if the heat index was expected to rise over 32 °C (90 °F) for a large part of the day, in order to avoid heat exhaustion. If temperatures were not expected to surpass 10 °C (50 °F), experiments were forestalled by difficulties with handling tools, vaporizing propane, and drying the wet ground after fire extinguishment.

2.8.2. Preparation

Preparation for a typical experiment began with clearing the test area of debris. The timber/mulch pans were connected and located at the prescribed distance from the shed and centered along the shed/wind machine centerline axis. Heavy steel bars were placed in the assembled pan at the leading edge and in the overlap region to weigh it down. The timbers were laid in the pans along the centerline (except for the angled timber experiments) with the downwind end located 1.83 m (6 ft) from the shed (when a shed was present). Some taller timber stacks required attachment of small steel angles at two locations on each side to keep the stack stably upright. If the protocol for the planned experiment prescribed mulch in the pan with the timbers, a 5 cm thick mulch layer was laid evenly and compressed by foot throughout the pan. Mulch was also then laid, spread evenly, and compressed in the target mulch pan at the base of the shed (when present), if prescribed by the test plan.

Preparations for instrumentation included positioning of the four or five video cameras with framing of the appropriate views. The bidirectional probe array was positioned in front of the windward end of the timbers. The burner was connected to the propane gas cylinder and was positioned on both sides of the timbers, with its leading torch head located 2.5 cm (1 in) from the upwind end. Half of the torches on the burner were aimed upward to the sides of the timber and the rest aimed downward toward the pan or mulch depending on whether mulch was present. The propane cylinder was opened, the burner line charged to adjust the burner flow, and then the gas was shut off with a valve. Before the first test on a given day, pneumatic zeroing of the pressure transducers was performed by connecting a short length of rubber tubing to each side of the bidirectional probes and recording the data. This also enabled troubleshooting any problems with the pressure transducer voltage outputs. A drifting voltage indicated a poor connection, and a voltage significantly different from 2.5 V indicated a probe plumbing leak.

After a safety check of the surrounding area, the wind machine was warmed up for approximately 5 min prior to each experiment. A garden hose was attached to a fire hose, which was in turn connected to a hydrant. The hydrant was opened to charge the line, and a diesel pump was started up to pressurize the hydrant with water from the nearby pond.

Finally, a safety briefing was conducted to communicate the test procedure, participant roles, and safety reminders. Zeroing tubes were removed from the probe array, and the test description and filename were detailed in the logbook.

2.8.3. Operations

The following procedure was typical, although some minor aspects varied for some tests. The data acquisition system was initiated with the selected filename and description. 15 s, typically, but sometimes as much as 60 s of background data were obtained before two stopwatches were started simultaneously and the program time was recorded. At that time, all video cameras were put into recording mode. After 50 s of stopwatch time, a small propane torch was ignited, and at 55 s the propane cylinder was opened. At 1 min, the ignition torch was held near the burner torches until they were all ignited. The times for initiating and completing burner ignition were recorded. For most experiments, the burner was sustained for 90 s on the timbers and mulch in order to produce a self-sustaining fire that would not self-extinguish or get blown out by the wind. Some conditions such as cold ambient temperatures (which diminished the propane flow) called for longer burner duration up to 3 min. Photographs of the timber and mulch fire such as the one shown in Fig. 13 were taken shortly after ignition.

A countdown to generating wind was performed, and a digital timer located next to the shed pan and visible in two or three of the video camera views was initiated at the same time as the wind machine was started. The wind speed was adjusted by setting the tachometer to 32π rad/s (950 rpm) for low wind (a nominal 6 m/s [13 mi/h]), 50π rad/s (1500 rpm) for medium wind (a nominal 10 m/s [22 mi/h]), and 67π rad/s (2000 rpm) for high wind (a nominal 14 m/s [31 mi/h]). The times for initiating the wind and completing its adjustment were recorded in the log. As soon as the wind started, the propane valve was closed, and the burner was removed to protect it from the fire.

In addition to the continuous videos recorded on fixed cameras, photographs were taken from many angles and fields of view during the experiment. The photos included the overall views encompassing the entire timber stack and shed, the linear extent of the fire along the timbers/mulch, spot fires in the target mulch bed, and unusual or interesting phenomena. Some interesting phenomena were captured using the video mode of the handheld digital camera.

The experiment ended when a spot fire in the mulch bed at the base of the structure reached the wall and after fire had also spread to the end of the timbers. Some experiments were ended before flames reached the end of the timbers because of the slow rate of fire spread and long duration of the experiment. Sometimes, flames at the wall from spot fires were extinguished if the fire had not yet spread over the entire length of the timber in order to capture the fire spread rate over the entire timber. At the end of the test, the fires were extinguished with a water hose and post-fire photographs were obtained.

2.9. Research Scope

This section describes the range of conditions that were investigated for this experimental series on landscape timber fires.

2.9.1. Parameter Summary

From May 2019 through November 2020, 16 field experiments were conducted on landscape timbers. Separation distance from the target shed (when present) was kept constant at 1.83 m (6 ft). Timbers varied by type, stack height, and orientation. Wind speed was varied on a limited basis.

Table 1 is the complete test matrix and shows the configurations and conditions for each experiment. Discussion and descriptions of these tests throughout the following sections will refer back to the Test No identifiers. The parameters and numbers of tests conducted under each configuration or condition are listed in Table 2 through Table 6. Table 2 lists the landscape timber types and various stacking arrangements tested for each type. Table 3 shows the distribution of experiments conducted with and without mulch in the pans holding the timbers. Table 4 shows the distribution of experiments conducted with and without a target mulch bed in which firebrands may potentially ignite spot fires and spread to the target shed. Table 5 lists the numbers of experiments conducted at each of the three wind speeds. Finally, Table 6 shows the experiments conducted with special configurations of landscape timbers regarding orientation and use as a retaining wall.

Table 1. Test Matrix

Test No.	Date	Element	No. Stacked	Nominal Wind Speed (m/s)	Shed	Target Mulch Bed	Mulch with Timber	Special
D4	6/4/2019	Thin	2	6	No	No	No	
D5	6/18/2019	Thin	2	10	No	No	No	
D6	6/18/2019	Thin	2	14	No	No	No	
D11	8/5/2019	Thin	4	6	Yes	Yes	No	
E3	11/6/2020	Thin	4	6	Yes	Yes	No	dirt/wall
D13	9/3/2019	Thin	4	6	Yes	Yes	Yes	
D25	10/30/2019	Thin	4	6	Yes	Yes	No	30°
D24	10/30/2019	Thin	4	6	Yes	Yes	Yes	30°
D10	8/1/2019	RR Tie	1	6	Yes	No	No	
D16	9/19/2019	RR Tie	1	6	Yes	Yes	No	
D15	9/9/2019	RR Tie	2	6	Yes	Yes	No	
D20	10/15/2019	RR Tie	2	6	Yes	Yes	Yes	
D2	5/22/2019	6×6	2	6	No	No	No	
D12	9/3/2019	6×6	2	6	Yes	Yes	No	
D21	10/15/2019	6×6	2	10	Yes	Yes	No	
D14	9/9/2019	6×6	2	6	Yes	Yes	Yes	

Table 2. Distribution of Experiments by Timber Type

Timber Type (nominal cross section dimensions)	Actual Dimensions	Stack Height	Number of Experiments
Thin (3 in × 4 in)	7.0 cm × 8.9 cm × 2.44 m (2.75 in × 3.5 in × 8 ft)	2	3
		4	5
		All	**8**
6×6 (6 in x 6 in)	14.0 cm × 14.0 cm × 2.44 m (5.5 in × 5.5 in × 8 ft)	**2/All**	**4**
Railroad Tie	17.8 cm × 22.9 cm × 2.59 m (7 in × 9 in × 8.5 ft)	1	2
		2	2
		All	**4**

Table 3. Distribution of Landscape Timber Experiments by Mulch Present with Timber

Mulch with Timber	Number of Experiments
Not Present	12
Present	4

Table 4. Distribution of Landscape Timber Experiments by Target Mulch Bed

Target Mulch Bed	Number of Experiments
Present	11
Not Present	5

Table 5. Distribution of Landscape Timber Experiments by Nominal Wind Speed

Nominal Wind Speed	Number of Experiments
6 m/s (13.5 mi/h)	13
10 m/s (22.5 mi/h)	2
14 m/s (31 mi/h)	1

Table 6. Distribution of Landscape Timber Experiments by Configuration

Configuration	Number of Experiments
Aligned with centerline	13
30° angle with centerline	2
As retaining wall with dirt	1

2.9.2. Separation Distance from Structure

When the shed was present, experiments were performed at a separation distance between the shed wall and the nearest end of the landscape timbers of 1.83 m (6 ft). Additional separation distances were not tested based on the results of the fence and mulch experiments [1], which showed that only short distances might have a slowing effect on fire spread rates. Figure 17 shows a photograph of the layout showing the shed, landscape timbers (in a wind-aligned configuration), and bed of shredded hardwood mulch which served as the target for spot fires. Also shown is the distance between the wind machine and windward end of the timbers, which varied slightly depending on which type (and length) of timber was being tested. The distance from the wind machine to the shed (or where it would be) was 10.67 m (35 ft) in every experiment. When there wasn't a shed, the landscape timbers were still located as if they were 1.83 m (6 ft) from the shed if it were there so distances of landscape timbers of the same type from the wind machine were consistent with and without the presence of the shed. This means that the downwind ends of all landscape timbers were always located 8.84 m (29 ft) from the wind machine. The position of the bidirectional probe array was always 1.22 m (4 ft) from the upwind end of the landscape timbers.

Fig. 17. A side view of the experimental setup including the target shed and mulch bed showing the separation distance of the landscape timbers from the shed and the distance between the wind machine and landscape timbers.

2.9.3. Wind Speed and Direction

Wind speeds through a community during a WUI fire event may span a wide range around the prevailing wind speeds. Local winds may be stagnant or may exceed prevailing wind speed, depending on local shielding and channeling due to structures, vegetation, and terrain. The experiments in this study were performed under nominal imposed wind speed conditions from

6 m/s to 14 m/s (13 mi/h to 31 mi/h), generated by a large fan with a tilted flow straightener as described in Section 2.2. Low, medium, and high wind speeds corresponded to average values along the centerline in the ranges 5 m/s to 9 m/s (11 mi/h to 20 mi/h), 10 m/s to 13 m/s (22 mi/h to 29 mi/h), and 14 m/s to 18 m/s (30 mi/h to 40 mi/h), respectively. Most experiments were performed at the low wind speed after early experiments at higher wind speeds exhibited difficulty for fires to remain ignited and spread.

All experiments with a shed present were performed with the shed wall perpendicular to the imposed wind direction. For most experiments, the landscape timbers were aligned along the centerline in the direction of the wind machine fan axis. Two experiments were performed with the timbers at an angle to the centerline.

2.9.4. Timber Arrangements

The three types of landscape timbers tested were described in Section 2.4. These timbers were stacked at different heights depending on type:

- The thin rounded pine timbers were stacked with the widest side facing down either 2 or 4 timbers high for total heights of 15.2 cm (6 in) or 30.5 cm (12 in), respectively. Due to the variable nature of the thin timbers' shape and degree of warping, the stacks varied up to 1 cm taller than the nominal heights.
- The larger square timbers were always stacked 2 high for a total height of 27.9 cm (11 in) with an uncertainty of about 3 mm (0.1 in).
- The railroad ties were stacked on their widest sides either 1 or 2 timbers high for total heights of 17.8 cm (7 in) or 35.6 cm (14 in), respectively. The railroad ties also varied in shape and size consistency with heights varying up to 1 cm.

Figure 18 shows photographic examples of the three timber types in their highest stacked configurations without mulch.

2.9.5. Retaining Wall

In order to compare the burning behavior of timbers with a realistic retaining wall configuration, for one experiment, a stack of four thin timbers was attached on one side to a frame of gypsum board that held a 7.6 cm (3 in) thick layer of dry dirt against the timbers. This configuration was intended to simulate a retaining wall holding up a bank of dirt, similar to a raised flower bed. The rest of the simulated raised bed was hollow and covered with a layer of gypsum board rather than dirt. For a worst-case scenario providing less of a heat sink for flames than dirt with higher moisture content, the dirt was dried in a 30 % relative humidity room and its moisture content was estimated to be <5 %. The test was conducted at low wind speed without mulch beside the timbers in order to compare it to a similar test without the frame and dirt on the side. Figure 19 shows three photographic views of the retaining wall configuration.

Fig. 18. Photographs showing examples of the three timber types: thin timbers (upper left), 6×6 timbers (upper right), and railroad ties (bottom).

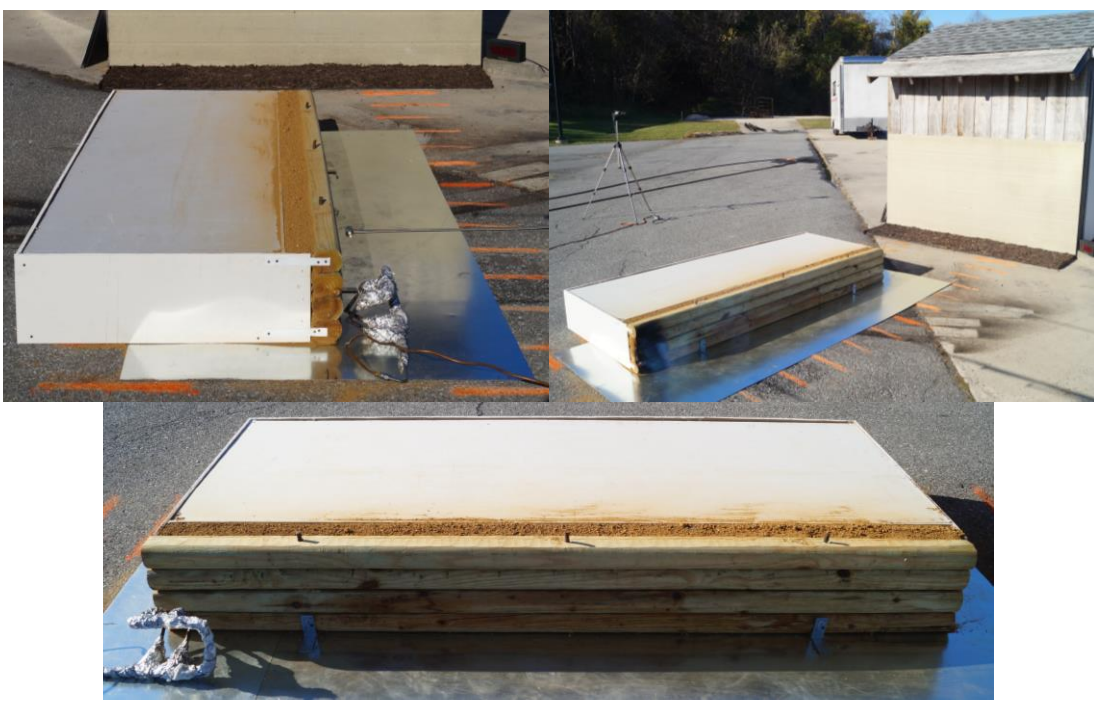

Fig. 19 Photographs of the thin landscape timbers configured as a retaining wall.

2.9.6. Presence of Mulch

Shredded hardwood mulch was placed along some landscape timber arrangements to compare the fire spread rate and spot fire ignitions with configurations conducted without mulch. The mulch represented any fine combustible material that might be adjoining the landscape timbers. Mulch was expected to enhance both fire spread and spot fire ignition, but whether this was true and to what degree were research questions for the study.

2.9.7. Orientation

All but two of the landscape timber experiments were oriented with the timbers along the centerline of the experiment, in line with the fan axis. Two experiments were conducted with the landscape timbers at a 30° angle to the centerline to see how the fire spread and spot fire ignitions were affected by the change in orientation. Figure 20 shows photographs of an experiment performed with the landscape timbers oriented at a 30° angle. The experiment centerline crossed the timber at its midpoint.

Fig. 20 Photographs of an experiment performed with the landscape timbers oriented at a 30° angle to the centerline.

2.10. Video Analysis

Every experiment employed four video cameras, with views from the left, right, left front, and right front of the object being tested, from the point of view of the wind machine fan (facing the shed). In some experiments, a fifth camera was used – to record the target mulch bed spot fires more closely, for example, or to record a closeup of an interesting phenomenon. The videos recorded the progress of flames and charring and the ignition of spot fires, as well as events such as burner ignition, wind machine engine startup and shutdown, and the start of suppression. The frame rate was 29.97 frames/s.

The analyses for the timing of spot fires in the target mulch bed and flames reaching the target shed wall were performed on videos from the left and right cameras. When the fifth video camera was employed from the left to focus on the target mulch bed, its record was used to observe the timing for these phenomena instead of the main left camera which captured a broader view including the landscape timbers.

The video records of the landscape timbers were analyzed to produce three important sets of data: fire spread rate along the landscape timbers, time to the first spot fire ignition in the target mulch bed, and time to spot fire flames impinging on the shed wall. To synchronize the data sets, the video sound records were analyzed to determine the time that the wind machine was started. This was done for cameras viewing both the left and right sides of the experiment.

The fire burning rate calculation also required the time that the wind machine was lowered to engine idle or was stopped, the initial extent of the burned length before the wind started, the final extent of burned length when the wind was lowered, and the time at which the flames reached the end of the landscape timbers, if this was the case. The rate was calculated by subtracting the maximum burned length from the initial pre-wind burned length and dividing by the difference between the time the maximum length was reached and the time the wind was started. The fire spread rate was calculated for each side of the landscape timbers. The set of timing and length data on one side was considered separate from the other, since ambient winds and other factors differed and each side burned somewhat independently.

To determine the time to the first spot fire ignition in the target mulch bed, each video was analyzed for the time at which smoke rose from the target mulch bed for the first spot fire that continued to burn (versus any that self-extinguished). The time the wind was started was subtracted from the ignition time to generate the time to first spot fire ignition. Both left and right video camera records were analyzed for these times, but the shortest duration from either camera (or from the extra left camera view) was used as the definitive time for an experiment.

For the time to spot fire flames impinging on the shed wall, both left and right video camera records were analyzed to determine the time at which flames reached the wall. The analysis was sometimes difficult due to heavy amounts of smoke generated by multiple spot fires and possibly the whole landscape timber stack by this stage of an experiment. The time to spot fire flames on the wall was determined by subtracting the wind start time from the time flames were observed on the wall. Again, both left and right and sometimes the extra left video camera records were analyzed, and the shortest duration was recorded.

2.10.1. Event Timing

All four or five video cameras monitoring the experiment were turned on shortly before the propane burner was applied to the test subject and turned off as the fire was being extinguished with water from a hose. Each camera view was fixed in place during the experiment after adjustment to capture the field of interest. To compare the views from multiple cameras, usually the right and left views, the timing was synchronized. The primary event used for synchronization of the videos and referencing the timing of spot fires and flames was Fan On. Fan On marked the zero time for all analyses, and typically occurred 3 min after the propane burner was ignited. Time zero was simply determined aurally from when the wind machine engine started (“caught” after “turning over”) which is a distinct sound immediately after the sound of the starter and “cranking”. This is easily determined within 1 s for combined expanded uncertainty.

As a backup reference for timing in case there was an issue with the audio or when multiple videos were used to capture an experiment, the initiation of the digital timer described in Section 2.7.2 and its continued operation were visible from the camera on the left side. For the landscape timber experiments, the timer was started at the same time as the wind machine. The time to ignite the burner typically took about 10 s since the hand-held torch had to be applied to 8 burner torch heads.

The timing of spot fires was measured for all of the experiments that included a target mulch bed. Two simple timing measures were determined for each experiment:

(1) the time at which the first spot fire ignited within the target mulch bed, and

(2) the time at which sustained flames were first observed at the wall.

The rationale for determining these events is the following. Flames on the wall indicate the earliest time at which a combustible wall could be ignited by a spot fire. The first spot fire puts the mulch bed and any other combustibles in or near the mulch bed at risk. Also calculated from these times was the length of the period between spot fire ignition and the time of flames reaching the wall.

The right and left video recordings were used to identify the first spot fire ignited. Ignition was detected when the first visible puff of smoke at a location was distinguishable from the surroundings. The spot fires were tracked back in time to determine the ignition time. Only spot fires that continued (did not self-extinguish) were counted. Spot fires that self-extinguished produced a small amount of smoke for a short time but did not grow or spread. These short-lived spot fires could not cause the ignition of other combustibles.

The time of flames on the wall was determined to be when flames began to lick the wall either continuously or more than two times within 5 s. This criterion was used to eliminate situations when there was a brief single flame that did not persist sufficiently to ignite the surface if it were combustible.

While timing was determined from video recordings from both sides, the earliest times (usually from the camera view closest to the spot fire or flames which provided the best visibility) were selected as the actual time of the event. The maximum expanded combined uncertainty for the times to spot fires was estimated at less than 4 s, but the uncertainty for the time to flames on the wall was estimated at about 5 s due to difficulties seeing the flames in the videos and judging when they began to consistently impinge on the wall. Calculation of these uncertainties took into account rounding errors to the nearest second and assessment of the difficulty of precisely determining the initiation time of smoke and flame from the videos.

2.11. Wind Field Description and Analysis

The fence/mulch report [1] provided an in-depth description of the wind field generated by the wind machine from both measurement/analysis and modeling perspectives. It explained the functionality and output of the software programs used to analyze and visualize the velocity measurements. In summary, for the fence/mulch experiments, the flow field was not uniform, but the velocities were within 20 % of the average with the lowest speeds at the probe nearest the ground and in the center where there is an area of lower wind speeds surrounded by higher ones, roughly in the shape of a doughnut due to the fan hub. The landscape timber experiment separation distance was held constant at 1.83 m (6 ft), which was the furthest distance from the shed used for the fences.

Appendix C.2 in the fence/mulch report [1] shows mean velocity profiles measured during experiments at four distances from the wind machine. The positions of the probe array corresponded to separation distances between the end of the fence or mulch bed and the shed of 0 m to 1.8 m (0 ft to 6 ft). In this study, the separation distance between the timbers and the shed was held constant. Appendix B has excerpted pertinent descriptions and analysis from the fence/mulch report and includes a description of the wind speed analysis and average plots for this distance. The resulting pseudocolor plots show that the velocity profile is reasonably uniform over the central region of the wind field in the region occupied by the landscape timbers. The center velocity is somewhat lower than the assigned wind speed and increased with distance along the mulch bed toward the shed due to the angled flow straightener. The lowest probe generally experienced the lowest velocities. Despite the lower velocities at the lowest probe position, the wind field did extend to the ground sufficiently to push the fire plume forward and cause fire spread horizontally and vertically when the wind machine was turned on.

The fence/mulch report also described flow simulations using the Fire Dynamics Simulator (FDS) [11] computational fluid dynamics software that helped understand the interaction of the wind with the structure and burning objects. With the wind perpendicular to the wall, a vortex is formed in front of the shed that causes a counterflow at the ground. Firebrands that enter the wind higher in the flow field are deposited closer to the shed wall, while those that enter lower are resisted by the counterflow and may be deposited at the front edge or side edges of the target mulch bed. This effect had less impact on the landscape timbers compared to fences since the timbers are lower to the ground in this study.

A cross-flow was added to the FDS model of the experimental setup to determine what levels of ambient wind speeds could be tolerated during experiments without significantly affecting the overall wind field and firebrand pathways. The modeling results informed the wind restrictions described in Section 2.8.1.

3. Experimental Results

The set of 16 experiments described in this report represents a survey of the effects of certain landscape timber configurations on the spread of fire to a structure, given various wind speeds and other conditions. The wind was perpendicular to the shed wall for these experiments. The focuses of this study were on fire spread along the landscape timbers, spot fires ignited by firebrands, and fire behavior particular to landscape timbers. Three timber types in multiple configurations were evaluated under a range of conditions; the parameters were described in Section 2.9.

Because of the large number of combinations and limitations on performing the experiments, only a couple of the experiments were replicated. The comparison of quantitative data was made more difficult because many phenomena involved in firebrand spotting, such as generation of firebrands and ignition processes, are stochastic in nature. The analysis of the data from this set of experiments was therefore focused on uncovering trends, rather than on quantitative results. The existence of trends could point to potential mitigation strategies.

Wind speed was generally set at the lowest level, but a small number of experiments explored the differences at moderate and higher wind speeds. Separation distance between the landscape timbers and the shed was fixed for all experiments for which the shed was present, and the distance was maintained between the timbers and wind machine whether a shed was present or not. This section will explore the effects of wind speed, timber type, timber stack height, and the presence of mulch along the base of the timbers.

Bar graphs are used to compare the results for different configurations and conditions. For wind speed, the conditions were low, medium, and high with nominal speeds of 6 m/s (13 mi/h), 10 m/s (22 mi/h), and 14 m/s (31 mi/h), respectively. Appendix B includes the wind speeds calculated for each experiment, which were calculated from the 4 lowest vertical bidirectional probe locations on the experiment centerline. The top (5^{th}) probe was nearly 2 m above the timbers where the wind speed did not interact with the timbers. Uncertainty for the average wind speed takes into account the uncertainty of the bidirectional probe pressure transducer measurement, the uncertainty in the correlation of the probe response to pressure, the uncertainty in the ambient temperature measurement, and the variation in the actual wind. The maximum combined expanded uncertainty on the values used for average wind speed was ±15 %.

The separation distance has a combined expanded uncertainty of ± 4 mm, which takes into account measurement error. For the separation distance of 1.83 m, this represents a 0.2 % uncertainty.

As described in Section 2.10.1, the combined expanded uncertainty for the timing of spot fires and flames on the wall was less than 4 s. The uncertainty for the time between the wall spot fire and flames on the wall was less than 5 s. Due to the difficulty in ascertaining the progress of the intermittent flames and burned area along the landscape timbers, the uncertainty in the fire spread rate along the timbers was estimated at about 5 % to 7 % for the timbers that burned the least extent and about 0.3 % for those that were fully burned.

3.1. Effect of Wind Speed on Fire Spread Rate

The low wind speed level of 6 m/s (13 mi/h) was selected as the primary wind for most of the experiments due to the thermally thick nature of the landscape timbers. The large masses of the timbers were expected to have difficulty sustaining ignition and flame spread with higher winds. A limited number of experiments were carried out at medium or high wind speeds to observe the effect.

Figure 21 shows the fire spread rate in m/h along two types of timbers for which the winds were varied. Both the thin and 6×6 timbers were stacked two high for the experiments that were compared. For each pair of bars graphed, the left bar is the spread rate calculated from the left-side video and the right bar is from the right-side video. The first three pairs of bars for thin timbers show a slight decrease in spread rate from about 1.7 m/h at the low wind speed to about 1.3 m/h at the medium wind speed. This decrease may not be significant due to the wide variation from test to test. The third pair of bars shows a fire spread rate of about 4.4 m/h for thin timbers at the high wind speed. This is a significant increase which can be attributed to the effect of the higher winds.

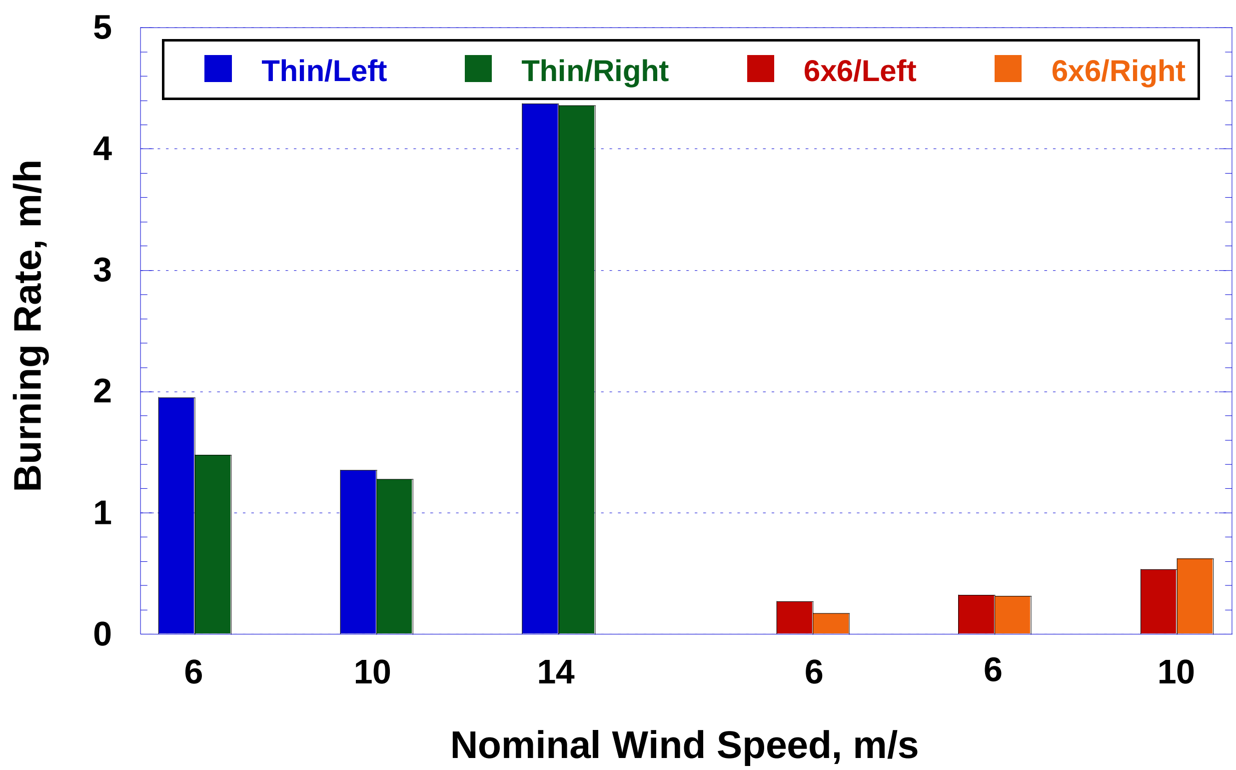

Fig. 21 A graph of burn rates observed for various timber configurations and wind speeds. All were 2-high stacks without mulch. (L to R): thin timbers at low, medium, and high wind speeds; and 6×6 timbers at low wind speed (two experiments) and medium wind speed. Left bars represent spread rates observed on the left side and right bars represent those on the right.

The next three pairs of bars in Fig. 21 show the fire spread rates for three 6×6 timber experiments with the first two under the same low speed wind conditions followed by a third conducted under medium winds. The first two experiments provide a measure of the variability of the spread rate under the same low wind conditions, with averages of 0.2 m/h and 0.3 m/h. The third experiment's spread rate of 0.6 m/h is sufficiently higher that the increase may be attributed to the higher winds. All three of the 6×6 timber experiments exhibited lower fire spread rates than the thin timber experiments, which demonstrates some basic differences between the two types of timbers. The thin timbers have less mass to heat up and have more cavities and spaces between them for flames to grow due to their curved cross sections.

The effects of wind speed variation on spot fire timing were not studied because two of the three experiments where the wind was varied did not involve the target mulch bed. Only one timber configuration with the target mulch bed was conducted at two wind speeds, which was not sufficient to draw general conclusions about the wind speed effects on spot fire ignitions and spread. This pair of experiments will be briefly discussed in Section 3.3 concerning configuration effects.

3.2. Effects of Timber Configuration and Mulch on Fire Spread Rate

This section explores the effects of timber type, stack height, timber orientation, and the presence of mulch with the timbers on the fire spread rate along the timbers. All of the wind speeds for the experiments compared in this section were low (6 m/s) unless otherwise specified.

Figure 22 is a graph of the fire spread rates from six thin timber experiments with left and right bar pairs for each. The first two experiments are without mulch, with the timbers stacked two high for the first experiment and four high for the second.F There is no significant effect of the stack height, with both spread rates about 1.7 m/h. The third experiment, with a stack of four timbers in the retaining wall configuration without mulch, only produced one data point because the burning only occurred on the right (exposed) side. The fire spread rate for the retaining wall configuration was significantly lower at 0.5 m/h. With ignition and flames only on one side and dirt on the other, there was no opportunity for heat transfer across the timbers or air penetration through the timbers that could have enhanced burning, as could occur in the experiments with both sides of the timber stack exposed to air and flames. Also, the large retaining wall frame of gypsum board provided significant blockage of wind from the left side of the wind machine, which could reduce favorable fire spread conditions on the exposed side.

The next pair of bars in Fig. 22 are for the experiment of thin timbers stacked four high with mulch present in the pan along both sides of the timbers. The fire spread rate (6.1 m/h average) was greatly enhanced in this configuration compared to the one with the same stack of timbers without mulch. However, the difference between the left side spread rate of 9.7 m/h and the right side rate of 2.5 m/h is significant. At the low imposed wind levels of these experiments, ambient winds had a significant impact on the relative fire spread rates of each side, with the side facing the ambient wind exhibiting a lower spread rate compared to the side away from the ambient wind.

The next two experiments graphed in Fig. 22 are for stacks of four thin timbers at a 30° angle to the wind machine and shed, without and with mulch, respectively. The fire spread rate without mulch (about 1.1 m/h) is between those for thin timbers in line with the wind without mulch and the retaining wall, also without mulch. The angled configuration seemed less favorable for fire spread compared to the in-line configuration. The second angled timber experiment in the presence of mulch showed a fire spread rate of 6.4 m/h, which is more consistent with that from the in-line configuration with mulch. The left and right rates, 6.9 m/h and 6.0 m/h, respectively, were much closer to each other than the spread rates on the two sides for the in-line configuration. With so few experiments, it is impossible to be definitive, but the penetration of wind through the stack of timbers suggests greater thermal and air communication across the stack than was observed for in-line timbers.

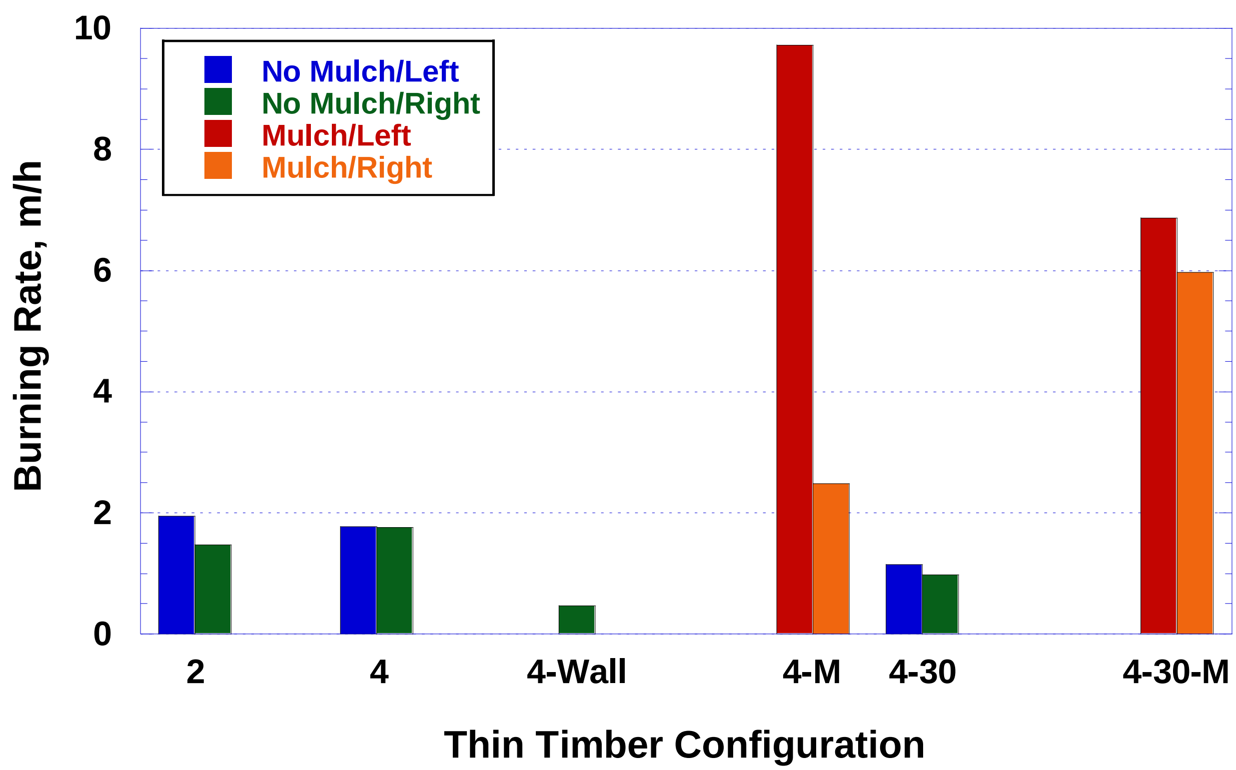

Fig. 22 A graph of burn rates observed for various thin timber configurations (L to R): 2-high stack without mulch, 4-high stack without mulch, 4-high stack as a retaining wall without mulch, 4-high stack with mulch, 4-high stack at 30° without mulch, and 4-high stack at 30° with mulch. Left bars represent spread rates observed on the left side and right bars represent those on the right (retaining wall configuration only had flame spread on the right). All wind speeds were low (6 m/s).

Figure 23 is a graph of the fire spread rates from experiments of various timber types, stack heights, and mulch conditions. All of the experiments compared in the figure were exposed to low (6 m/s) wind speeds. The first three pairs of bars are repeated from Fig. 22 but are included here for comparison to other experiments. The spread rates from stacks of two and four thin timbers without mulch are comparable between 1.5 m/h and 2 m/h, but they are both much higher than the spread rates of the two experiments of 6×6 timbers without mulch, which averaged between 0.2 m/h and 0.3 m/h. The next pair of bars is for 6×6 timbers with mulch which exhibited spread rates of 0.4 m/h on the left and 0.8 m/h on the right and averaged about 0.6 m/h. The mulch enhanced the fire spread rate of the 6×6 timbers to some degree (between a factor of the 2 and 3), but not the level of enhancement seen for the thin timbers of a factor of about 3.5. The next four pairs of bars are for railroad ties of single height (twice), 2-high stack without mulch, and a 2-high stack with mulch. The fire spread rates for the two single height railroad tie experiments averaged between 0.2 m/h and 0.4 m/h. The 2-high stack experiment spread rate was somewhat higher at 0.7 m/h. The final railroad tie experiment of a 2-high stack with mulch had a spread rate of about 0.5 m/h which was of the same order as the spread rate without mulch. There was no enhancement of the railroad tie fire spread rate due to the presence of mulch.

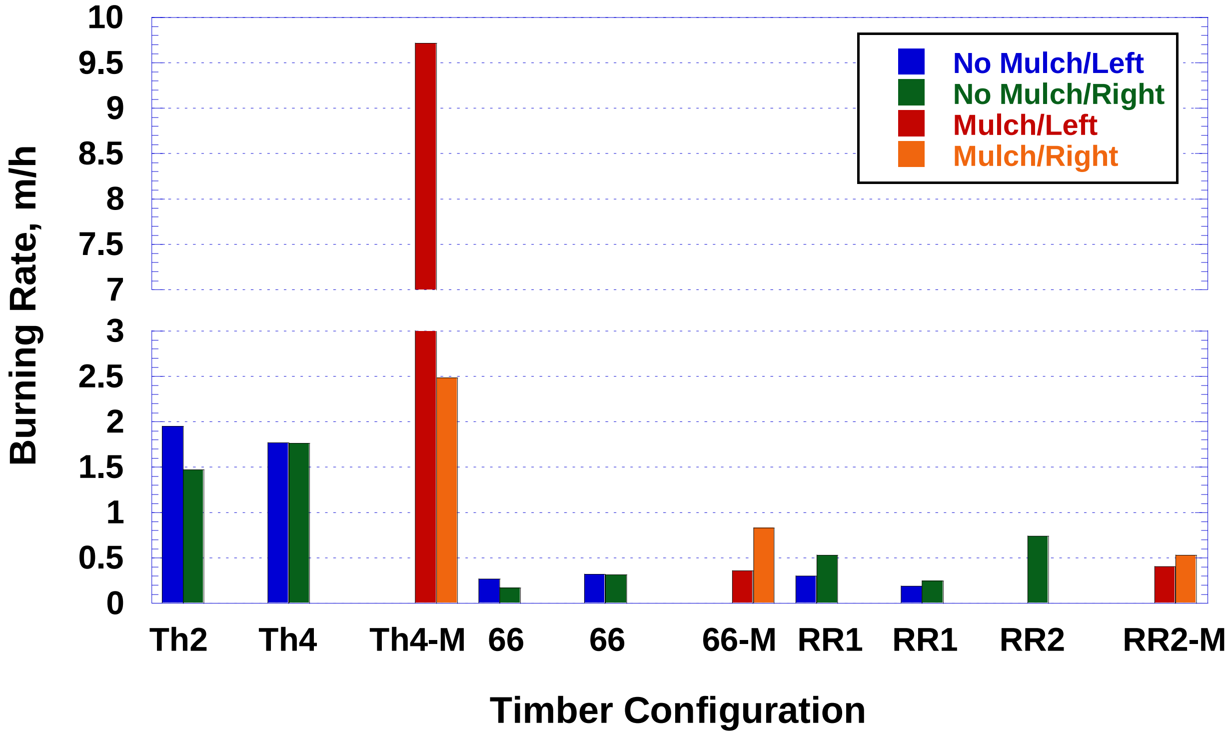

Fig. 23 A graph of burn rates observed for various timber configurations (L to R): 2-high stack of thin timbers without mulch, 4-high stack of thin timbers without mulch, 4-high stack of thin timbers with mulch, 2-high stack of 6×6 timbers without mulch (two experiments), 2-high stack of 6×6 timbers with mulch, single railroad tie without mulch (two experiments), 2-high stack of railroad ties without mulch (only right side burn rate available), and 2-high stack of railroad ties with mulch. All wind speeds were low (6 m/s).

3.3. Effects of Timber Configuration and Mulch on Spot Fire Ignitions

This section explores the effects of timber type, stack height, timber orientation, and the presence of mulch with the timbers on the timing of the ignition of spot fires and for flames reaching the shed wall. All of the wind speeds for the experiments compared in this section were low (6 m/s) except for one, which will be described later. Only two experiments with a target mulch bed did not generate spot fire ignitions: the 30° experiment without mulch and the retaining wall experiment, also without mulch.

Figure 24 is a graph of the time from the start of the wind for a spot fire to ignite in the target mulch bed and for spot fire flames to impinge on the target shed wall. For this graph, each pair of bars represents data from one experiment with the left bar showing the spot fire ignition time and the right bar indicating the time for flames on the wall. The second bar of each pair will always be greater than the first. The first two sets of bars are for 4-high stacks of thin timbers with the first set having no mulch and the second set with mulch. The times for spot fires to ignite were 45 min and 54 min for the cases without and with mulch, respectively. The corresponding times to flames on the wall were 84 min and 63 min, respectively. The next set of data is for the 4-high stack of thin timbers oriented 30° from the centerline with mulch present. The times for both spot fire ignition, 41 min, and flames on wall, 47 min, were both less than those times for both the no-mulch and mulch cases with standard timber orientation.

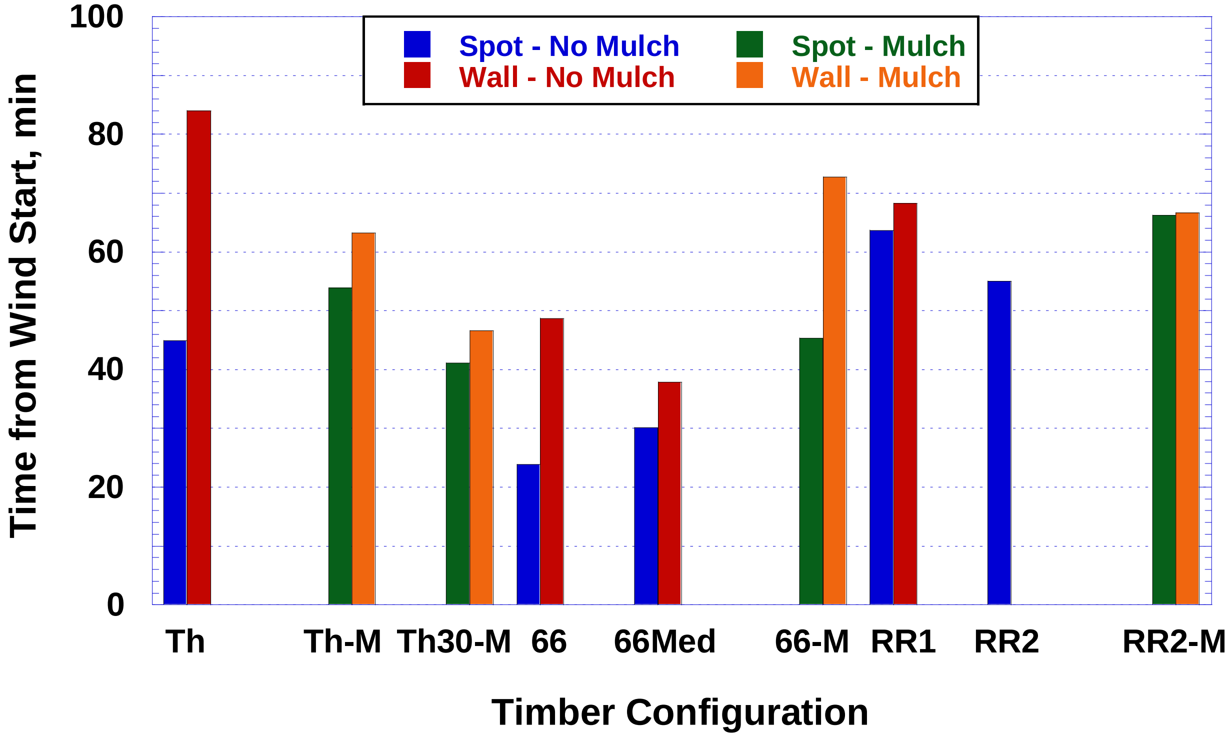

Fig. 24 A graph of the times for spot fire ignition and flames impinging on the target shed wall observed for various timber configurations (L to R): 4-high stack of thin timbers without mulch, 4-high stack of thin timbers with mulch, 4-high stack of thin timbers at 30 with mulch, 2-high stack of 6×6 timbers without mulch, 2-high stack of 6×6 timbers without mulch at medium wind speed, 2-high stack of 6×6 timbers with mulch, single railroad tie without mulch, 2-high stack of railroad ties without mulch, and 2-high stack of railroad ties with mulch. Except for the one experiment described with a medium wind speed, all others were conducted at low wind speed.

The next sets of bars in Fig. 24 are for spot fire ignition and wall flame times for 6×6 timbers stacked 2-high. The first two are for timbers without mulch. The only difference between them is that the second set was conducted at medium (10 m/s) wind speed (the only experiment on this graph not conducted at low wind speed). The spot fire time for the experiment at low speed was 24 min while the spot time at medium speed was 30 min. The wall flames time for the experiment at low speed was 49 min while the flames time at medium speed was 38 min. There is no obvious effect on the timing results for these two experiments due to the difference in wind speed. The next pair of bars is for 2-high stacked 6×6 timbers with mulch. The time for the first spot fire ignition was 45 min which is significantly slower than for the non-mulch experiments but is also counterintuitive since mulch usually enhances spotting as well as fire spread along the timbers toward the target mulch bed. This unexpected difference is probably simply a result of the widely varying stochastic nature of the fire spotting phenomenon.

The final sets of bars in Fig. 24 are for spot fire ignitions and wall flame times for railroad tie landscape timbers. The first two sets of bars are for timbers without mulch. The first experiment was for a single railroad tie and the second was for a 2-high stack of ties. There was no significant difference in the spot fire ignition times of 64 min and 55 min. The time for flames on the wall was not available from the 2-high stack experiments. The final pair of times was for a 2-high stack of railroad ties in the presence of mulch. The spot fire time of 66 min was comparable to those for ties without mulch. Due to its ignition location near the wall, the spot fire for this experiment reached the wall with flames less than 30 s after ignition. The time to flames for the 2-high stack tie experiment with mulch (67 min) was nearly identical to the time to flames for the experiment with the single railroad tie without mulch (68 min).

Once spot fires ignited in the target mulch bed, the source of timbers or mulch upstream should then have little effect on the progression to the shed wall. However, the differences in height and width of the timber stack could affect the flow patterns at the target mulch bed and have some impact on the spread of the spot fires. Figure 25 is a plot of the time between the ignition of the first spot fire and flames impinging on the shed wall. It shows the differences between the pairs of bars graphed in Fig. 24. As expected, the range and variety of times for the no-mulch condition is similar to that for mulch and there doesn’t seem to be a consistent pattern depending on timber type. One result that makes sense is the much shorter time for fire spread for the 6×6 timbers at medium wind speed (8 min) compared to those at low wind speed (25 min and 27 min).

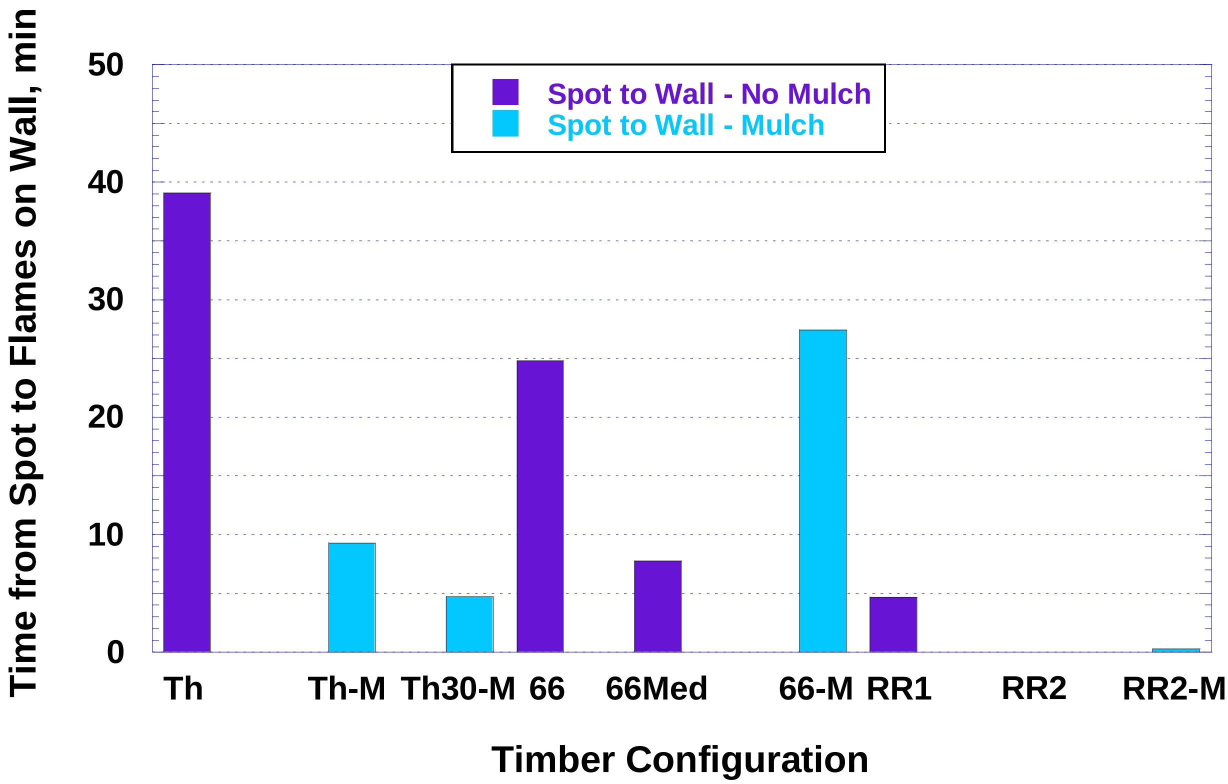

Fig. 25 A graph of the time from spot fire ignition to flames impinging on the target shed wall observed for various timber configurations (L to R): 4-high stack of thin timbers without mulch, 4-high stack of thin timbers with mulch, 4-high stack of thin timbers with mulch, 4-high stack of thin timbers at 30 with mulch, 2-high stack of 6×6 timbers without mulch, 2-high stack of 6×6 timbers without mulch at medium wind speed, 2-high stack of 6×6 timbers with mulch, single railroad tie without mulch, 2-high stack of railroad ties without mulch (no data), and 2-high stack of railroad ties with mulch. Except for the one experiment described with a medium wind speed, all others were conducted at low wind speed.

4. Discussion

Burning landscape timbers present a hazard to the residences in a community during a WUI fire, with exposures resulting from both firebrands and fire. In this study, a series of experiments on burning landscape timbers was conducted, with interest in both flame spread and firebrand production leading to spot fires. The results have been described in Section 3. During all but two of the landscape timber experiments that included a target mulch bed, and under a variety of conditions, spot fires ignited in the target mulch bed that spread to the shed wall. The parameters of the landscape timbers and test conditions were varied in order to evaluate whether any of them had a significant impact on the flame spread along the timbers or the timing of ignition of spot fires in the target mulch bed and flame spread to the shed. Conclusions are limited by the fact that there was only one test per condition and also by the stochastic nature of firebrand generation and ignition. However, some conclusions are strengthened when patterns are observed over multiple experiments, including the previous fence experiments [1].

Wind speed had some impact on the fire spread rate along the timbers. For thin timbers without mulch, the medium wind speed did not produce a higher fire spread rate than the low wind speed, but the high wind speed did significantly increase the spread rate. For 6×6 timbers without mulch, even medium winds seemed to cause a significant increase in spread rate, but 6×6 timbers have generally slow spread rates overall. Although only three experiments in this study were performed at medium or high wind speeds, the observation that higher wind speed accelerates the fire spread rate is in agreement with observations for the previous study on fences and mulch [1].

There were differences in fire spread rates due to landscape timber type. Thin timbers experienced faster spread rates than both 6×6 timbers and railroad ties, which had comparable spread rates. The lower amount of mass to heat and curved cross sections provided two reasons that the thin timbers burned faster than the larger, square-cornered types of timbers.

The presence of mulch sometimes enhanced fire spread rates depending on timber types. Thin timbers saw a factor of 4 increase in spread rate due to mulch and 6×6 timbers saw about a factor of 2 enhancement, but mulch did not appear to affect railroad tie fire spread rates. In this limited study, mulch appeared to affect fire spread rates less as the timbers increased in thickness and fit together more tightly.

Only three experiments were performed with different configurations for the timbers relative to the wind machine. The 30° angle orientation of thin timbers seemed to somewhat decrease their fire spread rate both with and without mulch. The orientation had no clear effect on spot fire ignition or spread. The retaining wall configuration of thin timbers definitely decreased the hazard as fire spread rate was slowed by having exposure to flames and air only on one side of the stack of timbers, having more mass (from the dirt layer) behind the timber surface to act as a heat sink, and possibly due to the extra wind blockage provided by the gypsum-board-covered frame representing the raised bed or higher ground being “retained.”

4.1. Hazardous Scenarios

The wind-blown firebrands from the burning landscape timbers in this study presented a hazard to the combustible target mulch bed in front of the target structure through spot fire ignitions and subsequent fire spread to the structure wall. This was observed in all but two cases in this study, across all the conditions that were explored. The fact that spot fires ignited and spread under all wind speed conditions puts landscape timber fires in a high hazard category, even though the timing for the spot fire ignitions is much slower than was exhibited by mulch beds, fences, and woodpiles. [1], [2]

In large WUI incidents, first responders may not be available to suppress in a timely manner (i.e. hours to days) a landscape timber or retaining wall fire that can impact downwind combustibles. If fire reaches the interior of a stack of timbers or retaining wall where water suppression has difficulty penetrating, it could take an extended time to extinguish the fire effectively. Ineffective extinguishment could allow smoldering to continue leading to reignition and additional fire spread. Despite the slow rate of spread observed in the specific configurations tested, the burning progression is sustained and would ultimately expose any connected or nearby combustibles. During WUI events, the linear nature of landscape timber fires could bring the fire to many structures and other combustibles via flames or firebrands before defensive actions by first responders could stop possible structure ignitions.

A more detailed discussion on implementing guidance based on the relationships among fuel layout, fire hazard, and structure hardening can be found in the NIST report entitled *WUI Parcel/Structure/Community Fire Hazard Mitigation Methodology* (HMM) [7].

4.2. Mitigation

This study focused on evaluating the hazards of burning landscape timbers from the spread of fire along them, the generation of firebrands that may cause spot fires in combustible materials downwind, and the phenomena of fire embedded in the timbers causing difficult extinguishment. No mitigation experiments were conducted. One could conjecture that having non-combustible sections or non-combustible barriers between lengths of timbers could slow or stop the linear progression of fire, a major negative behavior, along the landscape timbers. This may not be cost prohibitive if applied in a limited and strategic fashion. It was clear that the rounded corners of the thin timbers created cavities along their length that were beneficial to fire erosion and spread. Also, the rough, uneven, cracked, and creviced surface of the railroad ties provided locations for fire to embed, grow, and spread. Both of these timber types exhibited more deep-seated fires which required more water and careful extinguishment than required by the 6×6 timbers. Smooth-surfaced, square-cornered timbers such as the 6×6 lumber fit together tightly and created less opportunity for fire to ignite and be sustained. They also provide for easier extinguishment if burning. While there seems to be some advantage, these features have not been studied sufficiently for the potential advantages to be quantified.

One mitigation approach that is under consideration as a regulation by the California State Board of Forestry and Fire Protection is an ember-resistant zone around a home that would be required to have no combustible material. To be fully effective, the area would need to be maintained to remove any accumulated debris, and the effectiveness would be reduced if combustible materials accumulate at the base of the house during a WUI fire event with high winds after homeowners have evacuated. Some protective guidance (such as [12]) provided to homeowners in WUI-fire-prone areas already recommends this approach to diminish the likelihood of the ignition of spot fires near homes by firebrands from any source, including combustible wooden landscape timbers.

For a more comprehensive discussion of mitigation approaches for WUI fires, including the effectiveness of removing, reducing, and relocating the fuels and hardening the structures, see the *WUI Parcel/Structure/Community Fire Hazard Mitigation Methodology* (HMM) [7].

4.3. Limitations

This study was a survey of the fire behavior in wind of various configurations of landscape timbers that may be located near a structure. It illustrated some of the dominant and negligible factors related to the hazards posed by burning landscape timbers. An understanding of the limitations of this work will help to direct its applications. Limitations of this research include:

Insufficient testing to establish uncertainties: Only 16 experiments were conducted despite a large number of variables. This study was a survey to look for timber fire behaviors over a wide range of conditions, but experiments were not repeated to allow for establishing the range of variation in the fire behaviors under identical conditions.

The range of wind behavior was limited: These experiments were primarily conducted with steady wind at a low level in one direction relative to the landscape timbers and shed wall. A limited number of additional experiments explored medium and high winds and angled orientation of the timbers to the wind and shed. Flows around a structure from different angles will change the deposition pattern of firebrands. Real winds will gust over a range of speeds and directions, which could change the deposition of firebrands and potentially make the situation more hazardous. The winds in real events may be higher than those tested. In these experiments, the wind was not blocked by vegetation or landscape objects, which can induce swirl and areas of low pressure that might be favorable for firebrand deposition. In any case, the generation of firebrands presents a risk for additional fire spread.

The landscape timber configurations tested were not realistic in configuration or size: The landscape timber assemblies tested were relatively small compared to many typical arrangements. Many landscape timbers used for retaining walls are taller and sometimes involve vertical elements and multiple layers. Mulch or other combustible materials are often found at the top of such structures when used as retaining walls or for raised beds, and this material could significantly contribute to fire spread along the timbers. Larger and taller assemblies of landscape timbers will affect the local flow patterns which could impact the rate and direction of fire spread along the timbers and different patterns of firebrand deposition downwind. While burning, a larger quantity of wood may produce fire plumes such as were seen in the woodpile study [2], and the greater surface area will produce more firebrands for the wind to pick up and deposit, making larger assemblies potentially more hazardous.

The structure used was restricted in size: The target shed used in this study is smaller than a house and many other real structures. The height and width of a structure change the flow in front of and around it. Different relative angles of the wind will cause significant changes in the flow pattern as well.

The mulch represented a worst-case combustible target: The target mulch bed was a surrogate for any ground cover of fine combustibles such as grass, leaves, etc. It was used as a worst-case scenario. If there are no combustibles at all surrounding a house, then spot fires cannot ignite. CAL FIRE's proposed regulation for a new ember-resistant zone (Zone 0) within 0 to 5 feet of a home would attempt to address spot-fire prevention. Nevertheless, any vulnerabilities in the combustible surface of the structure itself provide potential sites for firebrand ignition. Hardening the home against firebrands would be necessary to address the hazard from firebrands generated from landscape timbers and other sources. Most existing houses have conditions somewhere between the extreme cases of combustible-free and hardened versus surrounded by combustibles and structurally vulnerable. Burning landscape timbers would pose a threat to any downwind combustible object that was close enough to ignite via flames or susceptible to ignition via firebrands.

Landscape timbers were ignited at a single location: The test protocol defined repeatable conditions in order to characterize landscape timber fire performance and identify any dangerous and potentially mitigating attributes. In WUI fires, however, incoming firebrands may ignite an assembly of landscape timbers at multiple locations, and at locations more or less favorable for fire spread. Multiple ignition locations could result in faster fire spread and firebrand generation. Ignition at the top of the landscape timber stack could result in slower fire spread, and the initially elevated fire could change firebrand generation and transport.

Ignition was by gas burner rather than a natural source: In these experiments, the landscape timbers were ignited at a focused area at ground level by a gas burner. The method differs from some natural ignitions in WUI fires in multiple ways. A gas burner is a severe ignition source, igniting by continuous flame contact and differing in heating rate and geometric extent from many natural ignition sources in a WUI fire. Natural ignition sources include single firebrands with sufficient mass and energy to ignite the timbers when deposited within cracks or crevices (direct firebrand ignition) and accumulation of debris such as leaves or twigs or a combustible ground cover that are ignited by a firebrand and produce flames sufficiently close to ignite the timbers (indirect firebrand ignition). The burner produced heat orders of magnitude greater than direct firebrand ignition and possibly several times greater than many indirect firebrand ignitions. However, like the burner's very localized, intense exposure, there is potential in real timber installations for a large radiative or flaming exposure from some other burning combustible (vehicle, bush, debris, fence, shed, etc.) that could ignite a large section of a retaining wall or a large, heavy timber.

The tested timbers were new, unweathered, made of pressure- or creosote-treated wood, and dried to one moisture level: Different wood species, deteriorated condition due to weather exposure and age (cracked, creviced, rotted, damaged), different treatments or being untreated, and different moisture contents may influence ignitability, flame spread, and firebrand generation.

5. Conclusions

This section lists the key findings, practical recommendations based on the findings, and recommendations for future work. The fence/mulch report [1], which was the first in this series of reports, listed 14 Key Findings, 7 Primary Recommendations, and 5 Recommendations for Future Work. The report on woodpiles added to those lists 4 Key Findings, 2 new and 2 reinforced Primary Recommendations, and 1 new Recommendation for Future Work. A major goal of this effort is to generate a unified set of conclusions related to NIST's series of studies of the hazards associated with various categories of landscape combustibles.

5.1. Key Findings

Landscape timbers exhibited fire behavior in the high hazard range. The fence report defined medium hazard for landscape combustibles as "very slow fire spread without flaming and little or no generation of firebrands", while high hazard was defined as "supporting fire spread and generating firebrands but not progressing to full involvement with large flames." [1] Landscape timbers exhibited fire behavior in between these two descriptions but closer to high with slow fire spread, small flames, and firebrand generation that consistently ignited spot fires. One consistent finding from the previous studies is repeated (F1), and there are 6 new findings described for landscape timbers. General findings are listed first and followed by configurations of decreasing hazard level. The list picks up with the next number after the findings from the firewood pile report [2]. The findings are labelled according to the following categories:

FH Fire Hazard

LS Life Safety

HR Hazard Reduction – materials, assemblies, implementation/housekeeping

IC Improved Characterization – recommended future work to characterize these fuels more fully

F1. As combustible materials are combined, the hazard increases disproportionately. (FH) As was seen in the fence and mulch study [1], fuel agglomeration provides significant increase in energy release and increases fire and ember exposures. For a stack of landscape timbers by itself, the fire spread rates were slow and firebrands generated spot fires after long periods of burning. When a combination of landscape timbers and shredded hardwood mulch was ignited at the windward end, the fire progressed more quickly in the direction of the wind. Spot fire ignitions did not seem affected by the presence of mulch with the timbers.

F18. Fire spread rates vary with timber type, wind speed, and configuration, including the presence or absence of mulch. (FH) This report provides data on multiple landscape timber types and configurations.

F19. Spot fires due to firebrands from landscape timbers may ignite downwind combustibles within 42 min with or without the presence of mulch. (FH) Firebrands capable of igniting spot fires downwind were generated by combinations of landscape timbers and mulch tested in this study. All landscape timbers with adjoining mulch caused spot fires in the target mulch bed. The only configurations that did not result in spot fire ignition were the retaining wall without mulch and the 30° oriented timbers without mulch. The wind field may deposit firebrands close to the wall of the structure. If a home is undefended during a WUI fire and not properly hardened, these firebrands may pose a serious threat to the home.

5.1.1. High Hazard Configurations

Some landscape timber and mulch experiments demonstrated slow fire spread with some flaming and a limited but consistent generation of firebrands.

F20. Adjoining fine combustible materials enhance the fire spread along landscape timbers to a moderate rate. (FH) The fire spread over landscape timbers in the presence of fine combustibles (i.e., mulch) was faster than without the fine combustibles. While the fire spread rates did not approach that of fences with mulch, the mulch did enhance the fire spread rates of landscape timbers by a factor of 3 to 4, resulting in rates in the 2 m/h to 10 m/h range. This enhancement affected thin and 6×6 timbers, while the railroad tie fire spread rates were not affected significantly by the presence of mulch.

F21. Landscape timbers generate firebrands that are capable of igniting spot fires in downwind combustibles. (FH) Spot fires ignited in the downwind target mulch bed in front of the shed in 24 min to 64 min without mulch adjoining the timbers and in 42 min to 66 min with mulch adjoining the timbers. These results indicate that landscape timbers are a medium hazard for spot fire ignitions whether or not fine combustibles are in contact with them or not.

F22. Suppression of landscape timbers can require excessive amounts of water and time/attention from firefighters. (FH) When firefighters need to extinguish landscape timber fires, the characteristics of the fires can require a lot more water and time than other burning combustibles and make full suppression difficult. Individual landscape timbers themselves can have cracks and crevices where recessed fires can be shielded from water and continue to burn. Multiple timbers together create even more cavities and crevices in the spaces between the timbers, especially when the interfaces are not flush and tight (like the 6×6s) such as the thin and RR tie timbers. When landscape timbers are used as retaining walls, the sides of the timbers against soil are extremely inaccessible for water suppression, so fire can continue to smolder and spread in difficult to reach and obscured areas. Besides requiring excessive water and time/attention, these fires may continue to burn after ineffective suppression efforts cease.

5.1.2. Medium Hazard Configurations

Some landscape timber and mulch experiments demonstrated very slow fire spread without flaming and little or no generation of firebrands.

F23. Without nearby fine combustible materials, the fire spread along landscape timbers is moderately slow. (HR) The fire spread over landscape timbers in the absence of fine combustibles was generally slow (< 2 m/h) and dominated by glowing combustion inside cavities and intermittent flames that stayed close to the surface. Fire progressed at a faster rate along landscape timbers without mulch than it did along fences without mulch. Fire spread on landscape timbers was enhanced (compared to fences) by the gaps and crevices on some timber surfaces (especially railroad ties) and under and between timbers. Smooth and flush interfaces between stacked timbers slowed the rate at which fire enlarged and spread in crevices. Fire eroded material and spread inside these cavities further and faster than fences without mulch, but not sufficiently fast to be considered a high hazard. It should be noted that it may be difficult to keep landscape timbers sufficiently clear of fine combustible materials to achieve the slowest fire growth behavior. Wind-blown debris such as leaves and pine needles may accumulate during a WUI event. Also note that even slow fire spread rates can lead to ignition of nearby or connected fuels, including structures, if suppression is not achieved in time.

5.2. Primary Recommendations

The results of this study add to a comprehensive effort to reduce the vulnerability of structure and parcels to fire and firebrands. A hazard mitigation methodology [7] has been developed with the goal of allowing structures in the WUI to survive fire and firebrand exposures without intervention by first responders. The recommended strategy is to balance a reduction of the exposure with increased hardening of the structure. The exposure may be reduced by removing or reducing the fuels or by relocating the source.

Removal of combustible peripheral landscape features and replacement with non-combustible versions is the most obvious method of mitigating the hazard presented by wooden landscape timbers. Often, the non-combustible choices are more expensive and not preferred due to the ubiquitousness of the wooden options. Nevertheless, it is the first recommendation:

R10. In WUI-fire prone areas, use non-combustible alternatives to wooden landscape timbers. There are non-combustible alternatives to landscape timbers that perform the same functions. Brick, concrete, stone, and metal alternatives are available for delineating flower beds, lawns, and gardens. For raised flower beds and garden plots and for use as a retaining wall, brick, concrete, and stone options are available.

There are not many measures short of removal and replacement that may reduce the fire hazard of existing landscape timbers. In addition to the non-combustible option, the following recommendation resulted from this study.

R11. In WUI-fire prone areas, if wooden landscape timbers are to be used, select the smoothest, tightest connecting timbers to minimize ignition and fire spread susceptibilities. This will not prevent ignition or fire spread, but it will decrease the ease with which an assembly of landscape timbers ignites. It will also provide, at least initially, fewer gaps and crevices where fire can erode into and spread on and within the assembly. As warping, gap creation, and cracking increase with timber age and weathering, replacement with newer timbers should be considered, again only if wooden timbers must be used.

In addition to the above recommendations that are specific to landscape timbers, other recommendations from the fence/mulch report [1] or firewood pile report [2] are reinforced by the findings in this report. They are repeated and emphasized for landscape timbers here:

R3. **Avoid proximity to other combustible fuels, to reduce fire intensity and limit fire spread.** Burning landscape timbers are a source of flames and firebrands that readily spread fire to nearby combustible materials. Fuel agglomeration increases fire exposures and reduces defensible space.

R7. **Harden structures against firebrands, to prevent structure ignition from firebrands produced by fences and other combustible sources.** Burning landscape timbers produce firebrands that are capable of spreading fire over long distances downwind.

R9. **Avoid proximity of landscape timbers to the residence and other parcel structures, as well as neighboring structures, to prevent direct ignition by flames or flame radiation.** Prevention of structure ignition from landscape timbers is a function of the size and location of the timbers and the structure's design, including construction materials and assembly. Structures need to be hardened against the fire hazard from both flames and firebrands (See R7). To prevent direct flame exposure from ignited combustible landscape timbers, they should not lead directly to or connect with a structure and should be set back from structures on the parcel and neighboring parcels according to local codes and wildfire remediation guidelines.

For more detailed recommendations on spacings of combustible elements including fences, woodpiles, and landscape timbers and hardening of structures and parcels, refer to the WUI Structure/Parcel/Community Fire Hazard Mitigation Methodology report [7].

5.3. Recommendations for Future Work

This study on fire spread of landscape timbers suggested additional research to improve mitigation and reinforced recommendations listed in the fence/mulch report.

S6. **Additional research is needed to identify effective methods to mitigate the landscape timber hazard in WUI-fire prone areas.** <u>Non-combustible alternatives for retaining walls would eliminate the hazard.</u> If landscape timbers are used, there may be potential mitigation solutions. One idea for disrupting fire spread would be to place non-combustible metal, or cementitious barriers between individual timbers along a border or retaining wall. These may not completely stop fire spread but could slow it significantly. Research would be needed to determine effective designs and optimal materials for these barriers. Such barriers would not diminish firebrand generation except for limiting or slowing the amount of wood burning.

Intumescent paints or coatings could potentially mitigate ignition and fire spread potential of landscape timbers; however, versions have not yet been formulated that are sufficiently weather-resistant. Development of weather-resistant coatings for fire protection and their effectiveness for wooden landscape timbers are areas requiring additional research.

There are many combustible landscape features that may contribute to fire hazards in a parcel or community. Future studies that add to the findings of this study and prior studies on mulch, fences, woodpiles, and sheds will inform existing and new codes, standards, and best practices.

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Appendix A. List of Abbreviations and Acronyms

AHJ
Authority Having Jurisdiction

AWG
American wire gauge

CFC
California Fire Code

FDS
Fire Dynamics Simulator

HOA
Homeowners Association

HMM
Hazard Mitigation Methodology

HRR
Heat release rate

HWM
Shredded hardwood mulch

IBHS
Insurance Institute for Business & Home Safety

NFPA
National Fire Protection Association

NIST
National Institute of Standards and Technology

PHRR
Peak heat release rate

RH
Relative humidity

rpm
Revolutions per minute

SSE
South-Southeast

SSW
South-Southwest

WUI
Wildland-urban interface

Appendix B. Wind Characterization

Measurements from the bidirectional probe array described in Section 2.6.1 provided wind speed data in a plane orthogonal to the direction of the wind flow from the fan. For each individual experiment, the data collected from each probe were averaged over time to determine the wind speed as a function of horizontal distance from the centerline and height above the ground. This appendix describes how the data from multiple experiments were combined to provide insights into wind speed contours as a function of nominal applied wind speed and probe array location between the fan and the shed. The uniformity of the wind field in the region of the burning landscape timbers was of particular interest.

This discussion is excerpted from Appendix C of the fence/mulch report [1]. The landscape timber experiments were conducted at one of the four separation distances analyzed for the fence/mulch experiments, so the wind analysis is a subset of that performed for the fence/mulch report.

B.1. Measurement Distance from Wind Machine

The geometry of the experimental setup is shown in Fig. B. 1. This diagram focuses on the location of the probe array relative to the wind machine, timbers, and target shed. The horizontal distance d_{wp} from the wind machine to the bidirectional probe array is equal to the distance d_{ws} from the wind machine to the shed minus the distance d_{ps} from the probe array to the shed, $d_{wp} = d_{ws} - d_{ps}$. The distance of the probe array from the target shed is equal to the distance d_{pf} of the probe array from the timbers plus the total length d_{timber} of a landscape timber plus the separation distance d_{sep} of the fence from the target shed, or $d_{ps} = d_{pf} + d_{timber} + d_{sep}$. Combining these equations results in d_{wp} as a function of separation distance, $d_{wp} = [d_{ws} - (d_{pf} + d_{timber})] - d_{sep}$.

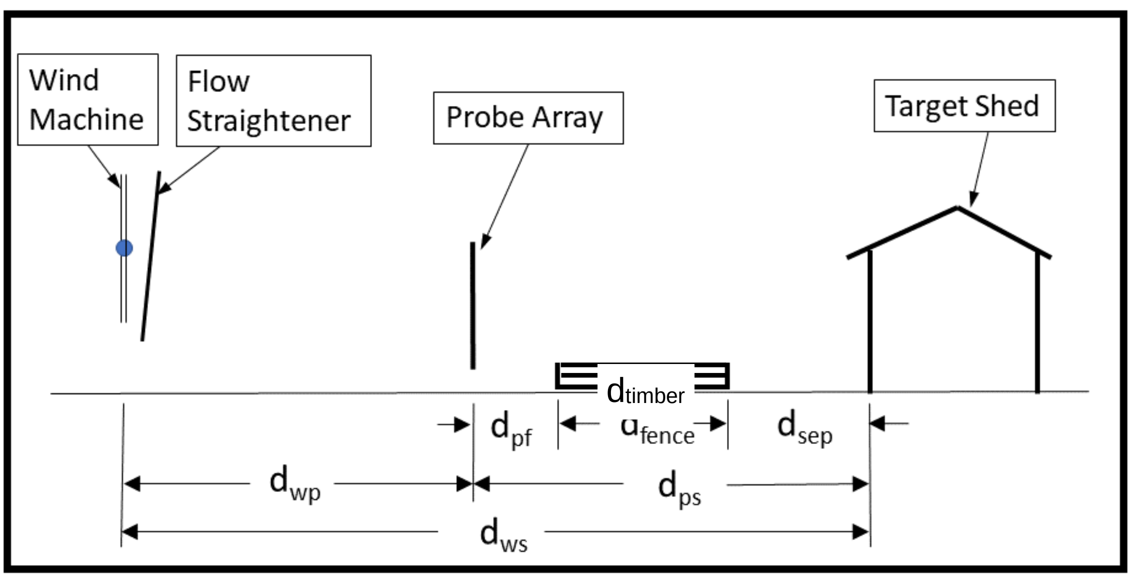

Fig. B. 1 Distances between experimental elements. Distances to scale.

For all experiments, d_{ws} = 10.67 m (35 ft) and d_{pf} = 1.22 m (4 ft). The length of railroad ties was 2.60 m (8 ft 6 in) which was within 2.5 cm of the 2.62 m (8 ft 7 in) length of a standard fence panel plus its posts. The length of the thin and 6×6 timbers was 2.44 m which put the probe array close enough to the location for the fences and railroad ties to not be able to distinguish differences in velocity profiles. The distance from the wind machine to the probe array as a function of separation distance is therefore $d_{wp} = 6.83\text{ m} - d_{sep}$, with all measurements in meters.

In Fig. B. 2, the locations of the probe array are highlighted for the four separation distances between fence/mulch and target shed used in the fence study. The position of the fence that corresponds to the longest separation distance, $d_{sep,A}$ = 1.83 m (6 ft), is shown in gray and is the same position as the timbers for this study.

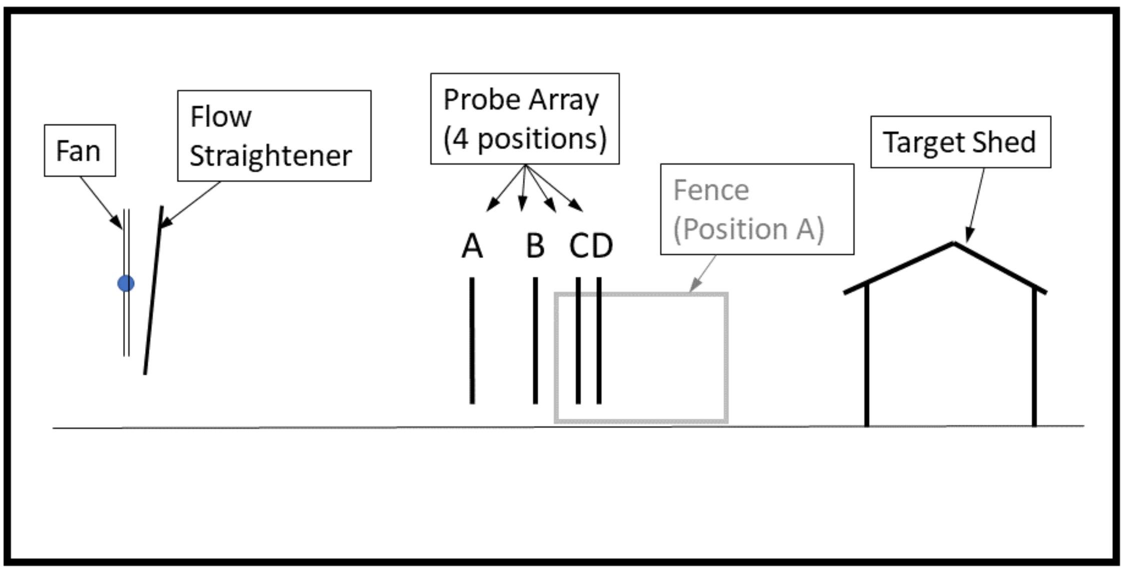

Fig. B. 2 Locations of bidirectional probe array for separation distances of (A) 1.83 m, (B) 0.91 m, (C) 0.30 m, and (D) 0 m. Distances to scale.

B.2. Wind Profiles

To calculate mean wind field profiles for the fence and mulch study [1] , experiments were divided into three wind speed levels (Low, Medium, High). A MATLAB program was written to calculate the means and uncertainties for the bidirectional probe velocities from individual experiments and in combination, and to display the results. In Fig. B. 3, the weighted mean values of the probe velocities are shown for the three nominal wind speeds and at the separation distance of 1.83 m (6 ft). The probe array for these experiments was located the nearest to the locations in this study. The data are displayed in pseudocolor plots, in which a matrix of colored cells on a gray background represents the wind speed value at each probe. Dots indicate the location of bidirectional probes. Velocity scales vary for each nominal wind speed. To get a clearer look at the variation of the mean wind speeds across the center of the flow field, weighted mean values of probes along the horizontal line 1.22 m (4 ft) above the ground and along the vertical centerline are plotted in Fig. B. 4 and Fig. B. 5, respectively.

The plots in Fig. B. 3 show the spatial extent of the wind field generated by the fan under each condition. The winds from the fan were felt over a region with a diameter of about 1.2 m (4 ft) approximately centered on probe 9, at 1.2 m (4 ft) above the ground. With the probe array at position A, at a distance of 5 m (16.4 ft) from the fan, there was a strong minimum at the center that corresponded to the hub of the fan. The uniform region extended from the ground to over 1.7 m (5.5 ft) above the ground. The profiles in Fig. B. 4 and Fig. B. 5 provide a more quantitative look at the wind speed data across the center of the profile horizontally and vertically.

The maximum Type A relative standard uncertainty value for the weighted mean wind speeds over all probes and all conditions of wind speed and location of the probe array was 0.0067. This is an order of magnitude smaller than the relative standard uncertainty for the bidirectional probe measurement of $u_{r,BP} = 0.0703$ from the velocity calculation from pressure and temperature. The uncertainty in the instrument measurement thus dominated the total uncertainty for the measured values of wind speed by the probe array.

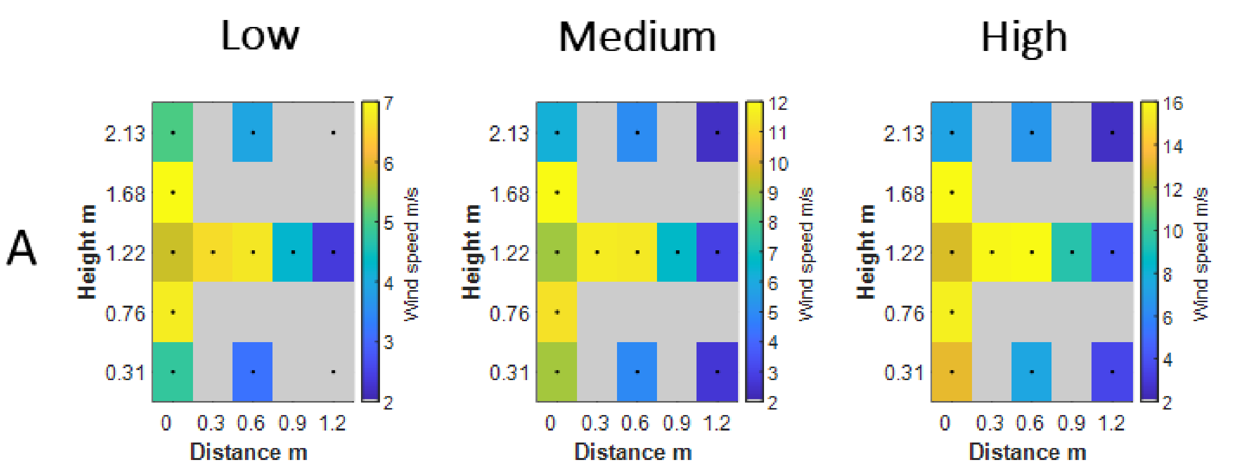

Fig. B. 3 Mean wind speed pseudocolor plots by wind speed and probe array location, over all fence and mulch experiments at a separation distance of 1.83 m (6 ft). Dimensions to scale.

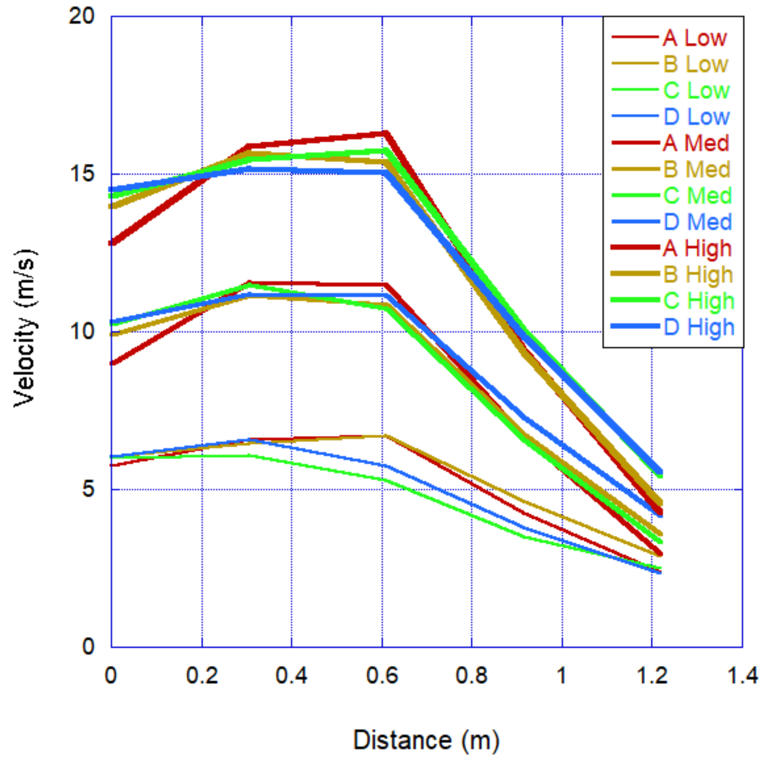

Fig. B. 4 Horizontal weighted mean wind speed profiles 1.22 m (4 ft) above the ground.

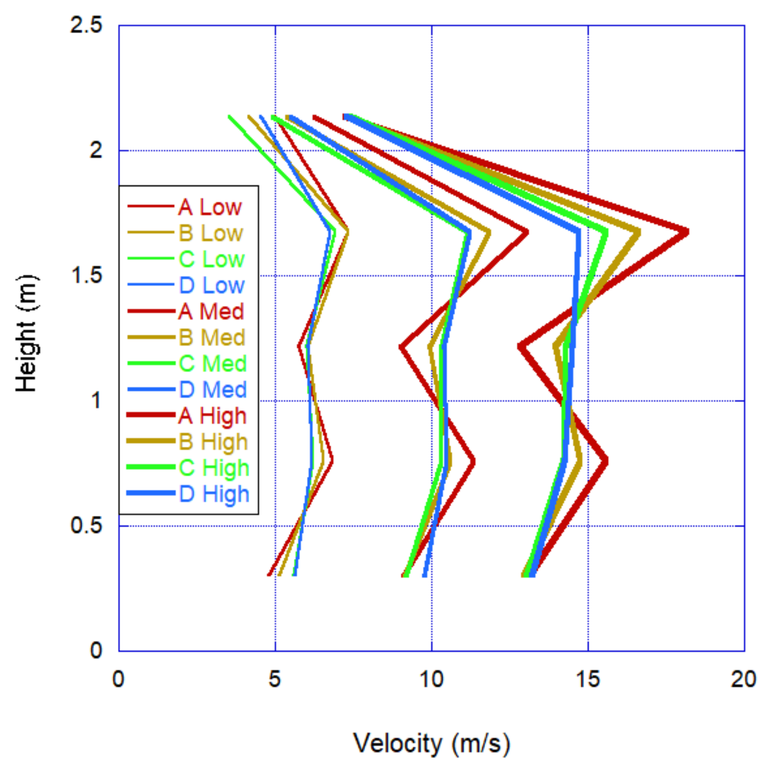

Fig. B. 5 Vertical weighted mean wind speed profiles along the centerline.