Multi-Scale Study of Ember Production and Transport under Multiple Environmental and Fuel Conditions

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I. Overview

A significant mechanism for wildland fire spread is ignition by embers lofted ahead of a flaming front (fire spotting). Little is known about ember production, transport and subsequent ignition of new fuel, despite the significant threat posed from flame spotting at wildland-urban intermixes and during intense burns. This is significant because ember production and subsequent fire spotting ignition data are needed for fire models used to inform fire management decisions. In this effort, ember production rates, sizes, velocities and temperatures will be determined using high-speed and infrared cameras. Visible and infrared images will be obtained and particle tracking software will be used to extract the ember data. Measurements will be collected for multiple vegetation and structural types, sizes, moisture contents, fire intensities, and wind speeds. This breadth of testing is enabled by experiments being performed at multiple scales ranging from the laboratory to prescribed burns. This will enable correlations between ember data from prescribed burns and more extensive measurements within the laboratory. Key parameters controlling ember production will be statistically determined from laboratory and field measurements. Correlations and data determined in this study will be used to implement an ember transport algorithm within a numerical wind modeling framework (WindNinja[1]) and shared with the fire community. The algorithm will simulate ember transport as a function of wind speed, direction and ember size, shape and density. WindNinja is currently used throughout the world to simulate surface wind flow in support of fire behavior simulations[2]. The coupled experimental and computational approach will provide essential data for modelling and wildland fire management, establish a methodology for multi-scale fire research, and provide a validated ember transport algorithm to increase the accuracy of models.

1. Project Justification & Expected Benefits

A significant mechanism for wildland fire propagation is spotting. During this process embers are produced, lofted in the fire plume, transported past the flame front, deposited, and if still hot enough can ignite the fuel beyond the actual front[3–6]. This method of flame spread is particularly significant for intense fires and at wildland-urban intermixes (WUI)[3,7]. At the latter location, embers which penetrate or lodge on homes can lead to ignition[8]. Ember production data from vegetative fuels has rarely been studied and understanding the role of embers at WUI is not well understood, despite its significance[3,9]. Ironically, many fire models depend on ember production as an input. Consequently, the predictive capability of the models is limited. ***In summary, there is a critical need to understand ember production, entrainment, transport, and ignition to strengthen fire management and predictions, develop safety policies, and optimize resource usage.***

Measurements of ember transport and production rates have been hindered by multiple challenges. First, it is difficult to directly measure. Moreover, production and transport rates may depend on multiple factors such as the type of vegetation, shape of the vegetation, moisture content, and wind speed. The limited studies of embers at wildland conditions have typically measured ember size distributions for a small number of fuel or environmental conditions[9–11]. While valuable, this data is not adequate to determine production rates, nor does it determine which vegetation and environmental factors control production. A second challenge is that ember production and transport should be determined at forest-scales. However, the extensive resources required for testing and the broad range of environment conditions limits the amount of testing which can be performed. An approach is needed to correlate small-scale ember generation and transport testing to forest-scale results.

The proposed research overcomes the aforementioned challenges to directly measure generation rates and transport distances for multiple fuels (vegetation and structural) and environmental conditions. This is done by applying high-speed visible and infrared imaging and participle tracking software to an extensive parametric study at multiple scales. ***Anticipated benefits from this effort include:***

1) Ember production rates, initial and final sizes, and velocity data for a variety of fuels (vegetation and structural) and environment conditions. This data will improve fire models.
2) The sensitivity of ember production and transport to different environmental and fuel conditions will be determined. This will allow fire management to better understand when propagation of fires caused by embers may occur.
3) Correlations of rate generation between small and forest-scale fires. This will establish a methodology for multi-scale testing which can be applied to future fire testing.
4) Temperature decay of embers near and downstream of the flame will be determined through direct measurement and heat transfer modelling. This will improve modelling efforts of ember evolution.
5) An ember transport algorithm incorporated into a surface wind flow model. This modelling tool can be used to inform fire management decision makers.
6) Transition of the discoveries to fire analysts and ecologists, as shown by letters of support.

2. Project Objectives & Hypotheses

It is hypothesized that ember production rates, transport, and sizes are primarily controlled by a few parameters (e.g. fuel/vegetation type, ambient wind speed, and fire intensity) and that results obtained at large-scales are correlated to results collected at small-scales. The following tasks will be used to evaluate the hypotheses:

1) Measure the size of embers and rate of production for different fuels and environmental conditions.
2) Determine the environmental and fuel conditions which control ember production.
3) Quantify ember temperatures at and downstream of the source of generation.
4) Establish a methodology bridging data and correlations from small-scales to forest-scales.
5) Correlate ember size, shape and density to transport distance, deposition rate and ember deposition temperature.
6) Establish a link between ember sizes, shape, and density to the inherent capacity to ignite fuels.

An additional task will transition results to fire management decision makers.

7) Integrate experimental findings and algorithm into a computational tool (WindNinja) for predictive modelling.

3. Relation to Task Statement Research Questions

The research tasks will specifically address the following questions posed by the solicitation:

1) What is the rate of ember production? Are ember production rates related to commonly used environmental indices?
2) What is the characteristic size and shape of embers under a range of conditions?
3) How far can embers of characteristic size and shape travel under a range of wind speeds?

4) How long can embers of characteristic size and shape burn and at what intensities?

II. Methods

1. Study Design

The challenge of understanding fire spotting in the WUI can be broken in to three questions: 1) what is the rate of ember production including their size, shape and density; 2) how far are embers lofted; and 3) are they capable of initiating combustion when they land? This study will address these questions by measuring ember sizes and production rates at multiple scales, determining the factors which control production, and then measure the lofting distance and the potential for ignition when they land. Measurements will be linked to a computational model that will predict ember lofting distance and temperatures. The coupling of the experimental and computational aspects of the study are illustrated in Figure 1.

Ember production rates and sizes will be studied in small- (1-5 kg of fuel), medium- (10's of kg of fuel), and large-scale (100's of kg of fuel) experiments as well as operational prescribed burns (1000's of kg of fuel). Ember transport measurements will be collected at the latter three scales. During small-scale testing, more extensive and controlled studies will be performed to ascertain key parameters that control ember generation. The sensitivity of ember production to parameters such as wind speed, vegetation or building material type and size, fuel moisture content, and fire intensity will be determined, as described in subsequent sections. It is possible that the various parameters may have a coupled effect on ember generation and transport. This coupling can be overlooked if only one parameter is varied during an experiment. A Design of Experiments approach will be used to statistically determine which parameters are coupled and significant, without requiring testing of each combination. A similar approach was recently used to isolate key parameters critical to combustion within gas turbine engines[12].

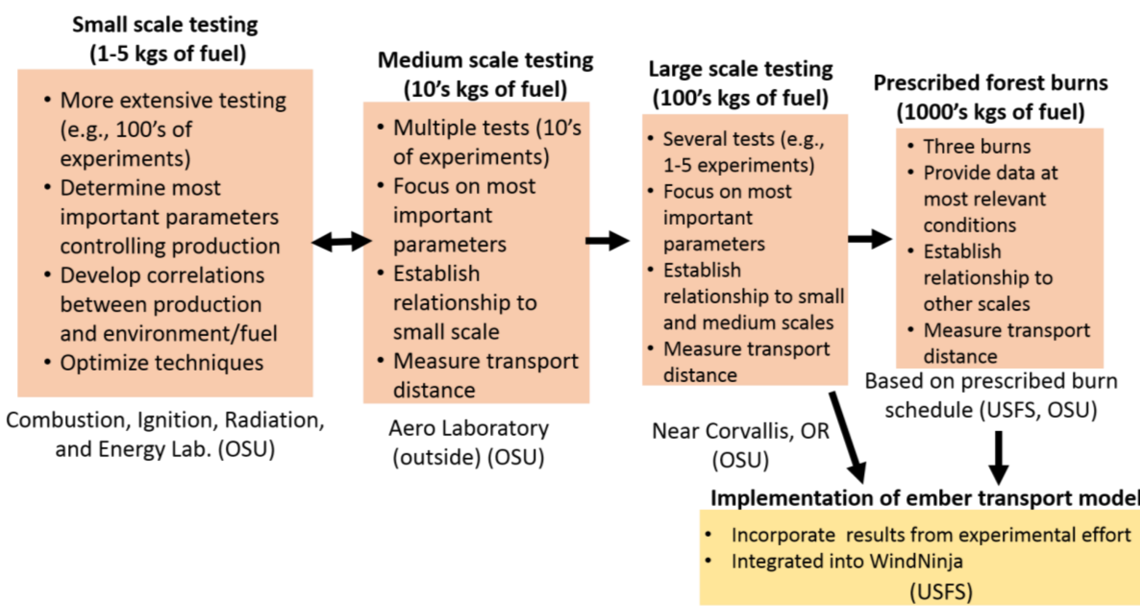

Figure 1. Approach for investigating ember production and transport through multi-scale experiments and coupling results with an ember transport model.

During medium- and large-scale testing, the same measurement techniques will be applied to larger quantities of vegetation or building materials. The parameters of the most importance (based on small-scale testing) will be investigated at larger scales. Ember sizes and lofting distances are expected to increase predictably with scaling. A key aspect of the study is that the larger-scale tests will be performed multiple times.

Three prescribed burns in forests will be performed over two summers as concluding validation. The location of the burns will be aligned with burns planned by regional fire managers. The measurement techniques and analysis performed at the smaller scales will be applied at the burns along with techniques developed and led by the US Forest Service. This will provide data at high-intensity burn conditions. Results from the different scales will be correlated and the methodology for a multi-scale approach will be evaluated. A letter of support for data collected during these studies is included from the Forest Service Regional Office fire analysis for the Pacific Northwest.

Correlations and data determined in this study will be used to implement an ember transport algorithm within a numerical wind modeling framework (WindNinja[1]) and shared with the fire community. The algorithm will simulate ember transport as a function of wind speed, direction and ember size, shape and density. Details regarding the algorithm and WindNinja are discussed in the Modelling Efforts section. The coupled experimental and computational approach provides essential data for modelling and wildland fire management decision support.

2. Study Sites

This section describes the experimental arrangements and test locations. A suite of measurement techniques will be applied at each location to measure the ember production rates, transport distances, sizes, velocities and temperatures, as discussed in the next section.

Figure 2 illustrates the two experiments which will be performed in the Combustion, Ignition, Radiation, and Energy Laboratory at Oregon State University. The top panel illustrates the approach for investigating the ember production characteristics of discrete pieces of fuel. Individual pieces of material (vegetation or structural) are placed above a flat flame burner. The burner generates a flat flame and provides a consistent ignition source. A fan will create varying cross-flow velocities, representative of those occurring at larger scales. High-speed and infrared cameras will collect data, as detailed in the next section. With ember characteristics determined for discrete pieces of fuel, similar measurements will be collected with groups of fuels, as shown in the bottom panel of Figure 2. A pile of the fuel will be placed in a perforated dish and ignited using a small torch and allowed to freely burn. A fan placed at the bottom of the pan will create a flow, representative of a strong updraft. Measurements will be collected for different fuel characteristics and flow velocities. Results from the laboratory study will: 1) provide a baseline for comparison at the larger scales, and 2) allow key parameters controlling ember production to be determined.

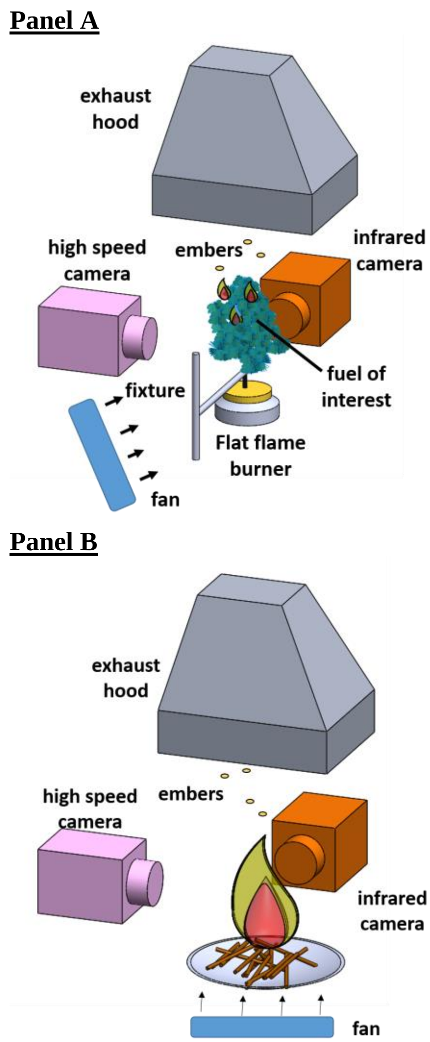

Figure 2. Experimental arrangements for studying ember production characteristics of pieces of materials (top) and piles of material (bottom).

The experimental arrangement for determining ember production at medium- and larger-scales and prescribed burns is shown in Figure 3. Similar to the laboratory efforts, two cameras will face the fire to quantify ember production, sizes and velocities. Water pans will collect ember samples at progressive distances from the fire. The medium- and large-scale testing (10's and 100's of kg) will be performed outside at the Aerospace Laboratory and OSU Research Forest where safe (previously burned) areas are available for free release of embers. Letters of support for the effort are included from the Aerospace Laboratory facility manager and the Director of the College of Forestry Research Forests. Medium size branches, small trees, and structural materials will be burned individually, as well as in mixed piles. If the cameras are not able to view the flame with sufficient spatial resolution, then only a portion of the flame will be viewed and the results appropriately correlated.

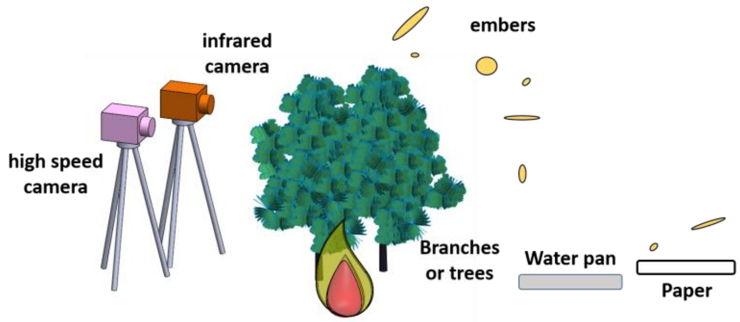

Figure 3. Arrangement for studying ember production and transport at larger scales and at prescribed burns.

For the prescribed burns (largest scales) the research team will coordinate with Fire Management Officers (FMO) in Forest Service Regions 1 and 6. The team will negotiate with FMOs to select the burns that show the greatest promise of successfully providing opportunities to measure ember production and transport distances. At least two different vegetation types will be targeted. Both imaging and *in situ* techniques will be applied and data correlated. Imaging techniques (which have limited field of views) will collect measurements over a subset of the burn. The i*n situ* measurements will include direct measurements of fire intensity, near ground plume vertical velocities, lofting distances of embers, and the potential for embers to burn through a paper layer when they land.

Development and implementation of the ember transport algorithm will be performed at the US Forest Service Rocky Mountain Research Station. This location has the required expertise and computational resources.

3. Field Measurements

Ember production rates and sizes, and the velocity at which embers are lofted, will be determined from images collected using a high-speed camera (Tasks 1 and 2). This data will be collected in statistical quantities for varying fuels, fuel sizes, fuel moisture levels, fire intensities, and wind speeds. The generation rate will be determined from images by tracking the number of particles which pass a specified distance from the flame, using image tracking software. Figure 4 illustrates a series of high-speed images of a fire with wood and pine needles. The first three

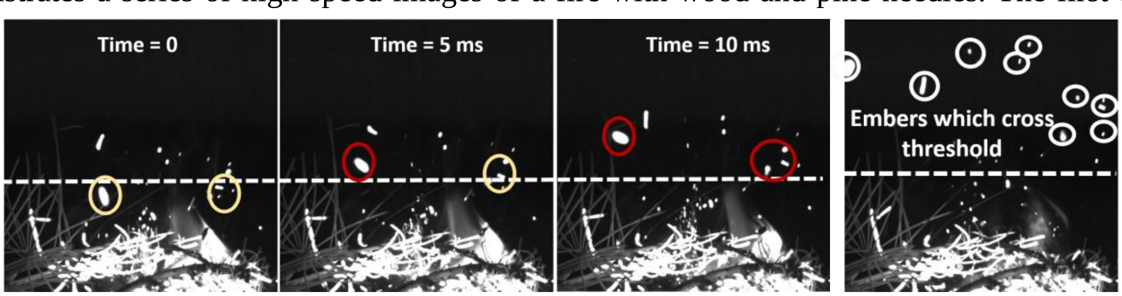

Figure 4. Illustration of ember tracking using high speed images. Four embers are "produced" (i.e. crossed the threshold) during 10 ms, as shown in the third panel.

panels illustrate four embers passing above the threshold and being considered "produced" over 10 milliseconds. The fourth panel shows all of the embers which have been "produced." This approach will allow the rate of production to be determined over the lifespan of the fire and be correlated to the parameters mentioned previously.

The velocity, direction, and size of particles will be determined using image tracking software, as conceptually shown in Figure 5. During data reduction, consecutive images are compared and statistical processes are used to determine the displacement of embers. The characteristic velocity is determined by dividing the displacement distance by the time between images. The size of the embers will also be determined from the images. Thus, velocity measurements will be correlated to ember size. Changes in the size of embers measured above the flame and collected in water pans will be compared, for a subset of experiments.

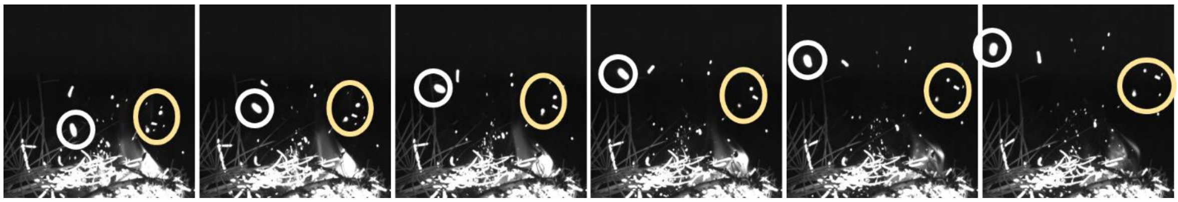

Figure 5. Illustration of ember movement being tracked. The velocity and direction are determined from the distance the embers move and the time between images.

The temperature of embers will be estimated using an infrared camera for a subset of tests. This information is used to understand how the temperature changes with time and distance from the flames (Task 3). Temperature data for pine embers (small dots) is shown in Figure 6. Note that temperatures are estimates because the emissivity of the embers was not determined in this preliminary effort. Temperature measurements of embers will be collected just above the flame and then at locations downstream.

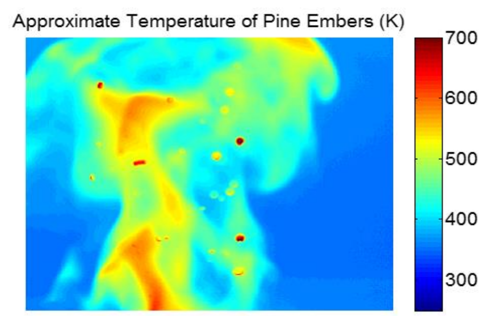

Figure 6. Estimated temperature of pine embers (small dots). The surrounding regions are radiation emitted by combustion products.

Several other key variables will be measured to establish correlations. The velocity of the co-flow is determined using a pitot tube or a hot-wire anemometer. The moisture content of the fuel will be determined from the dry-weight difference. The size distribution of embers collected in water pans will be found by spreading the samples on a uniform background and taking pictures. These pictures will be analyzed using image analysis software to determine the apparent surface area of the embers.

Similar approaches will be employed at prescribed burns. Infrared cameras are used to track ember production rates. A field deployable, fire resistant, programmable sensor array mounted in a fire resistant enclosure and coupled with a video imaging system is used to characterize *in situ* fire intensity, horizontal and vertical velocities, and energy release rates. This system reduces the safety risks and has been successfully used over hundreds of deployments. The system measures incident total and radiant energy flux, gas temperature, flame emissive power, and air flow. Moreover, the sensor system has been coupled with a digital video system[13].

Ember transport distances and landing ignition potential (Tasks 5 and 6) will be assessed by deploying paper or plastic sheets (1.3 m wide by 3 m long) covering metal collection trays at various locations downwind of the fires. The hypothesis is that embers insufficiently hot enough to burn through the paper or plastic are not hot enough to ignite vegetation. Ember lofting distance will be determined by spacing the paper receptors at progressive distances away from the fire front. Video cameras housed in fire proof housings will be placed to record ember deposits on the paper sheets (for prescribed burns), thereby eliminating the concern that sheets may ignite or be overrun by a fire front and destroy evidence.

4. Sampling Design

Experiments to measure ember production rates, sizes, velocities, and temperatures will be repeated multiple times for a subset of the conditions during laboratory tests. This data will be used to determine the statistical confidence of the measurements using a student-t distribution and assuming a 95% confidence interval [14]. This statistical information is used to estimate the uncertainty of the measurements (using a Chi-squared distribution) during the other tests, when repeated measurements are not practical.

The parameters (e.g. fuel, moisture content) which are varied during the small-scale testing will be determined using a Design of Experiments approach [12]. This will allow the most important parameters controlling ember production to be statistically determined. Results from the small-scale testing will be used to inform the conditions studied in larger scale experiments.

5. Data Analysis

The ember size, velocity and production rates will be determined from the high-speed images using particle tracking software. Correlations between ember production rate and fuel composition, size and moisture content, air speed, and fire intensity will be analyzed using a R^2 and residual fit analysis. This will allow the parameters which control ember production to be determined (Task 2). These parameters will be used to evaluate which environmental indices (e.g. Haines Index or Energy Release Component) are significant to ember production. Nondimensional numbers, such as the ratio of the ember mass to the fuel mass, will be evaluated to allow greater flexibility in scaling the results.

Ember deposition rates and ignition potential will be assessed through direct observation (either visually or through video recording) of ember deposits on paper sheets. As with ember production assessments, correlations will be developed between fuel type, fire intensity, wind speed, distance from fire front, and other environmental factors.

The data and correlations developed for small-scale flames will be compared to those for large-scale fires. The conditions which have the greatest influence on ember generation in laboratory studies will be replicated (as much as possible) in large-scale fires. Data collected for the different scales will be compared, and correlations between results for small and large scales will be developed (Task 4). This will establish a methodology for a multi-scale fire research.

6. Materials

The materials that will be burned at the different scales are shown on in Table 1 (next page). Vegetation and building materials are representative of those for ember production at the WUI.

Ember generation can vary for different vegetation types. In the interest of research success, this effort focuses on vegetation types found in the Northwest. Efforts will be made to study ember characteristics of two or three distinct vegetation types.

7. Modelling Efforts

A critical product from this effort is the development of an ember production, transport, and deposition algorithm (hereafter referred to as the 'ember algorithm') within the WindNinja numerical wind modeling tool (Task 7). Correlations between ember production, transport distance and deposition rates with fire intensity, wind, and vegetation descriptors will be developed from the laboratory and field studies. These correlations will be used to develop parameterizations for ember production, transport, and deposition in WindNinja. Outputs from the ember algorithm will include ember deposition patterns and density.

A source term for ember production will be included in the WindNinja model as a function of wind, vegetation, and fire conditions. This source term will be based on parameterizations derived from the experimental studies. The code will work as follows. WindNinja will first compute the wind field (as described in[1]) and will then use this information with vegetation data and a user-specified fire conditions to compute source terms for the domain. These source terms will be represented as a distribution of ember particle sizes within each grid cell. Transport and deposition of the embers will be modelled through a particle tracking algorithm. The algorithm will be developed in-house or based on the open source computational fluid dynamics libraries in OpenFOAM. The algorithm will compute trajectories of embers by considering buoyancy from the heat of the fire, advection by the mean flow field, and a force. The particle tracker will use parameters based on ember size, shape, and density developed from the field and laboratory studies to determine whether or not the particle is still burning at the time of deposition.

The WindNinja interface will be updated to accommodate the user-specified input fire condition and any additional inputs required by the ember algorithm. Ember deposition and density outputs will be available in the same output formats currently offered for 2D fields in WindNinja, including .kmz (viewing in Google Earth), .shp and .asc (viewing in GIS programs). Using these output formats strengthens the ability of fire managers. The outputted ember deposition patterns and density can be implemented in fire growth models in future studies.

Table 1. Vegetation and building materials to be burned at the different testing scales. The external parameters which will be varied are shown as well.

	Small-scale		Medium-scale		Large-scale		Prescribed burn
	Forest Product	Building Materials	Forest Product	Building Materials	Forest Product	Building Materials	Forest Products
Material	needles, bark, pinecones, twigs or branchs	plywood, particle board 2x4s	branches or small trees	plywood, particle board, 2x4s	large pile of branches or small trees	large pieces of plywood, particle board, 2x4s	forest
Other parameters to vary	moisture, content, velocity	velocity	moisture content				

III. Project Duration and Timeline

The project will last three years. Project milestones and timeline are shown in Table 2 (next page). Early efforts will focus on developing and conducting ember production and deposition measurement techniques. The next phase will consist of conducting laboratory and field studies. The final phase will consist of concluding experimental campaigns, developing and implementing the ember algorithm, summarizing findings and publishing and archiving results.

IV. Project Compliance - NEPA and Other Clearances

The field measurement portion of this project will be conducted in conjunction with prescribed burns planned and led by other organizations who have met required NEPA and related requirements in their respective burn plans. Therefore no additional clearance is required for this effort. Brian Jensen, the facility manager for the School of Mechanical, Industrial, and

Manufacturing Engineering, and Stephen Fitzgerald, the Director of the College of Forestry Research Forests, have agreed to support the proposed work at OSU (letters of support enclosed). Note that no human testing or sampling is associated with this project, thus an Institution Review Board (IRB) is not required as this project does not have a social science aspect.

Table 2. Illustration of project milestones and timeline.

	2015	2016				2017				2018		
Milestone/Description	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer
Set up experimental arrangement												
Refine techniques and processing												
Laboratory burns at OSU												
Medium-scale burns at Aero-Lab												
Large-scale burns in Oregon												
Collaborative field studies												
Analyze data												
Integrate algorithm into WindNinja												
Use WindNinja to predict ember transport												
Prepare and submit reports and papers												

V. Research Linkage

Table 3. Current and pending related research grants.

Grant Program	Project or Proposal Description/Identification	Funding Amount	Completion Date
National Fire Plan (Butler)	Upgrade of WindNinja	540K	9/30/2015
JFSP (Wagenbrenner)	Development and evaluation of high resolution simulation tools to improve fire weather forecasts	460K	Pending
National Science Foundation (Butler)	Assessment of utility of high resolution scanning LIDAR systems for providing early warning to fire management.	350K	Pending
JFSP (Viegas-Butler and team collaborators)	Development of new understanding into mechanism of fire spread due to ember spotting.	700K	Pending
PNW Research Station (Bailey)	Fuel management strategies and landscape-level fire risk transmission	411K	06/2017
PNW Research Station (Bailey)	Ecological effects of wildland fire in the PNW	211K	06/2015

VI. Deliverables and Science Delivery

Table 4. Schedule for completing and submitting project deliverables.

Deliverable Type (see proposal instructions)	Description	Delivery Dates (Months from initiation)
Year 1 report	Summary of efforts at lab and field levels	12

Year 2 report	Summary of efforts at lab and field level including success and failures	24
Final Report	Summary of findings from the study including description of how the work has been implemented as an operational support tool.	36
Conference presentations	Summary of findings from field study on production and deposition rates.	15, 30
Peer reviewed publications	Summary of findings from field study on production and deposition rates.	20, 34
MS or Ph.D. Thesis		36

VII. Roles of Investigators and Associated Personnel

Table 5. Roles and responsibilities of associated personnel.

Personnel	Role	Responsibility
David Blunck	Principal Investigator	Lead experimental research, advise student, analyze data, prepare deliverables
Bret Butler	Investigator	Lead prescribed burn study focused on determining production and deposition rates as function of fire intensity, fuel type and environmental conditions.
John Bailey	Investigator	Mentor student, lead efforts to collect and prepare fuel samples
Natalie Wagenbrenner	Post-doctoral associate	Facilitate integration of field and lab data into the ember transport model based on WindNinja surface wind modeling tool.
PhD Student	Researcher	Prepare and perform experiments, analyze data, develop correlations
Student (0.1 FTE)	Researcher	Collect and prepared samples, measure moisture content

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