Project Title: Evaluation and Optimization of Fuel Treatment Effectiveness with an Integrated Experimental/Modeling Approach

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I. Abstract

The effectiveness of a hazardous fuel reduction treatment must take into account both the physical change on fuel loading and structure and the effect that this change may have on wildland fire behavior. We first took a remote sensing and field measurement approach to quantify the effects of an aggressive fuel treatment program on fuel structure and loading. We then implemented laboratory and field campaigns designed to parameterize and benchmark the Wildland Fire Dynamics Simulator (WFDS), and conducted simulations aimed at eventually evaluating how changes in fuel loading and structure influence fire behavior. Findings from this research highlight: 1) the additional benefit in fuels reduction resulting from repeated fuel treatments vs. single prescribed fire operations in the under- to mid-canopy, 2) Forest floor consumption is predictable using only pre-fire loadings while canopy fuel consumption is much more dynamic, 3) Pitch pine live fuel moisture content, seasonality, and cohort age interact to result in variable needle flammability though the year, 4) Simulations with WFDS indicate that fuel moisture content and the choice of canopy drag coefficient had the most significant effects on model prediction, and 5) While WFDS can simulate moderate to high intensity fires, recreating low intensity fires with reduced fuel loading requires further refinement of the model.

II. Background and purpose

Between 2001 and 2011 approximately 5.6 billion US$ was spent on hazardous fuel reduction to treat an average of 2.5 million acres per year across the United States (Gorte 2011, NIFC 2011). These expenditures represent one of our nation's primary strategies for the mitigation of catastrophic wildland fire events. At the local scale, the placement and implementation of fuel reduction treatments is complex, involving trade-offs between environmental impacts, threatened and endangered species mitigation, funding, smoke management, parcel ownership, litigation, and weather conditions. Because of the cost and complexity involved, there is a need for implementing treatments in such a way that hazard mitigation, or other management objectives, are optimized. The level of commitment to this strategy also mandates that we clearly understand and evaluate the impact that we are having in affecting a change in fuels and fire risk across the nation. Changing climate, invasive insect infestations, and increasing human population add further impetus to these efforts.

The principals behind fuels treatments are generally well understood in the literature, and are summarized by Agee and Skinner (2005). Most extreme fire behavior events are the result of surface fire transitioning to shrubs or tree canopy through vertical fuel components; reducing the probability of these transition events is the primary goal of the majority of fuel treatment operations. However, a fundamental lack of methodologies to rapidly assess vertical fuel structure, at even the plot level, has severely impacted the systematic development of our knowledge base with regard to various treatment impacts on these fuel components. Additional difficulty arises because we are unable to rigorously test if the forest structure resulting from treatment operations is effective at slowing the spread or reducing the intensity of a wildland fire in any type of repeatable, or safe, way in the field. Quantifying the efficacy of fuel reduction treatments across heterogeneous landscapes-- the scale of most problem fires -- adds additional complexity. Replication and manipulation in the field is extremely difficult and expensive, if not effectively impossible at any appreciable scale, and therefore, the modeling of these scenarios in a computing environment provides an effective alternative. Until recently, however, numerical models were unable to integrate these three dimensional structural components into simulations due to computational and time scale constraints (Morvan 2011).

Our study integrated field sampling, remote sensing methodologies, and numeric modeling of fire spread to test the principals and physics behind fuel reduction treatments. First, we measured landscape-scale fuel loading using airborne laser scanning (ALS) and field census techniques, then conducted re-measurements to directly measure the consumption of fuels during prescribed fires in three-dimensions. We also linked the landscape-scale dataset with a spatially explicit prescribed burn history to understand the long-term effects of treatments on fuel loading and three-dimensional arrangement. Then, in order to understand the linkage between fuel reduction treatments and the subsequent effects on fire behavior, we also initiated a parallel study with the goal of using the Wildland-Urban Fire Dynamics Simulator (WFDS), a computationally intensive model that can simulate fire spread and intensity, to simulate treatment effects under consistent and representative meteorological conditions. Further, we conducted laboratory- and field- scale experiments to parameterize and benchmark WFDS for this task. While the initial simulations of fuel treatment effects could not accurately reproduce observed fire behavior, these efforts have identified key gaps in our knowledge of combustion processes and the importance of embers in the propagation of flame fronts in wildland fires (and have formed the basis of a successfully funded SERDP proposal). Overall, this project has contributed remote sensing methodologies, improved fire environment sampling methodologies, measurements of both forest floor and canopy fuel reduction treatments, and the identification of fundamental questions that will lead to the improvement of WFDS.

Project Objectives

1) Quantify the effect of fuel reduction treatments on three-dimensional canopy fuels and forest floor loading over a variety of treatment regimes at the landscape-scale via the integration of remote sensing and field measurements.

2) Implement and evaluate WFDS using coupled laboratory and in-situ observations of the fire environment.

3) Simulate and evaluate fuel reduction effectiveness by integrating measured distributions of fuel loading found at the landscape scale into WFDS to determine the optimal degrees and configuration of treatments. Ultimately, we will compare the advantages and limitations of this approach with the more commonly used semi-empirical models (Finney 1998).

III. Study Description and Location

A. Study area

We worked within the Pinelands National Reserve of New Jersey (PNR), specifically in Ocean and Burlington Counties. The PNR presents a near ideal set of conditions for this study because of the flat topography, simple forest community types, and intensive, well-documented fuels management activities (both RxB and mechanical) that are conducted on an annual basis (Clark et al. 2009). Three ecological factors contribute to the high wildfire frequency and intensity found in the NJ Pinelands: 1) forests are moderately productive and rapidly accumulate hazardous fuels, despite the low soil nutrient status of sandy, coarse-grained soils (Clark et al.

2009, 2015), 2) epicormic budding by the dominant pines, Pitch (*P. rigida*) and Shortleaf (*P. enchinata*) and prolific resprouting of shrubs and scrub oaks following disturbances contributes to "ladder fuels", which facilitate the transition of surface fires to the canopy, and 3) the sandy soils have a low water holding capacity, resulting in highly dynamic fuel moisture contents. We focused on upland Pitch pine-dominated stands which differed only slightly by the proportion of pine or oak in the overstory, and had similar mid and understory species composition. This area averages 1500 wildfires that burn approximately 7500 acres per year (NJFFS, 1930 to 2010). Large crown fire events occur here ca. every 5-10 years. The most notable major event occurred on the weekend of April 20-21, 1963, when wildfires burned 183,000 acres of forest, destroyed or damaged 186 homes and 197 buildings, and were responsible for 7 deaths. More recently, a wildfire burned 19,225 acres in Ocean County in 1995, and during the late spring of 2007, 15,550 acres burned near Warren Grove and the Garden State Parkway. As a result, fuel reduction treatments are viewed as essential wildfire management practices in this area. The NJFFS and Federal land managers conduct prescribed burns on ~ 16,000 to 24,000 acres per year. These activities are vital because of high population density on the edges of a growth-restricted core area, thus presenting urban-interface issues directly adjacent to nearly continuous fuels (Skowronski et al. 2016). Because of the heterogeneous fuels created here by high frequency of fuels treatments and wildfire, this landscape represents the ideal opportunity to evaluate fundamental questions with regard to long-term, landscape-scale fuel treatment effectiveness.

B. Landscape-Scale Fuel Treatment Effects

We estimated the effects of prescribed fire (RxB) treatments on three-dimensional fuel structure and loading across the PNR by taking an integrated (i.e., remote sensing and field census) approach. We collected airborne laser scanning (ALS) data for ca. 2000 km^2 of the PNR as a base-map (t_0) of canopy fuel loading across this landscape in year 1 and took a space-for-time approach using a database of prescribed burn and wildfire events across the landscape (LaPuma, in review) with ALS data-products to evaluate the effects of these treatments on three-dimensional fuel loading. Additionally, following the implementation of prescribed burns in years 1 and 2 ALS was collected again (t_1 and t_2) to measure the effects of the RxB on canopy fuel loading within the burn units. These ALS data were processed to represent canopy fuel loading following Skowronski et al. (2011). Surface and understory fuel sampling was conducted in conjunction with the ALS collections. Surface, understory, and canopy fuels were measured before and after each RxB treatment using a combination of destructive harvest and allometric methods.

C. Numerical Simulations with the Wildland Fire Dynamics Simulator

To evaluate the effectiveness of RxB treatment effects (the alteration of fuel structure and loading) on mitigating wildland fire spread and behavior, we used the Wildland Fire Dynamics Simulator (WFDS), a physics-based, computational fluid dynamics model. The implementation of this model first required extensive parameterization and evaluation within the pitch pine/ scrub oak fuel type. We then attempted to alter fuel loads within the WFDS environment and simulated otherwise identical ignition and environmental conditions to obtain model predictions of the change in fire behavior within the simulated extent.

a. Model Description

WFDS is an open-source computational fluid dynamics model (CFD) developed jointly by NIST and the USDA Forest Service (Mell 2010) for application to wildland and WUI fires. It is an extension of NIST's structure fire model, the Fire Dynamics Simulator (FDS), which has been progressively developed for over the past 25 years. The model solves a 3-dimensional form of the Navier-Stokes equations using Large Eddy Simulation (LES) to model turbulence. Atmospheric data is used to dictate appropriate boundary conditions. Vegetation is treated as solid particles which can be constructed into various geometric configurations throughout the computational mesh. Changes in vegetation due to fuel treatments are easily simulated. Thermal and physical characteristics of vegetation are needed as inputs in order to dictate the behavior of the fuel consumption, combustion, heat transfer, and drag models (Mell et al. 2009). The time dependent solutions for physical variables (such as temperature and velocity) can be visualized with the Smokeview tool (Forney 2010).

b. Laboratory experimentation for model initiation

This component of the project consisted of laboratory experiments that, when combined with field measurements (as below), contributed to the full implementation of WFDS. These studies provided fuel particle and bulk fuel properties. These laboratory experiments focused on the fuel particle and combustion properties of overstory *P. rigida* live and dead needles. In particular, the effects of fuel moisture content and seasonality of the needles were examined using the Fire Propagation Apparatus.

WFDS was initiated with the fuel properties that are necessary to represent the specific fuels of PNR. The particle properties were obtained in the laboratory by applying previous protocols to the fuels specific for our studies (Tihay et al. 2009, Bartoli et al. 2011). Following the development of the model parameters above and the integration of the meteorological and spatial data products obtained for the prescribed burn experiments, WFDS was initiated, run, and benchmarked against the fire characteristics observed in our field experimentation. This allowed for investigation of the sub-models of WFDS related to the combustion of the fuels specific to the PNR.

c. Field Evaluation

In order to initialize and evaluate WFDS we conducted three highly instrumented burns with the assistance of the New Jersey Forest Fire Service. The first two of these burns were moderately intense with instances of torching and some crowning (Figure 2, Ex1 and Ex2). The third burn (Ex3) was conducted in the same stand where Ex1 had been conducted two years previously. The blocks were fired with single ignition lines and burned with the prevailing wind. More information is available in Mueller et al. (2014) and Clark et al. (2016).

Fuels were measured before each experiment using a combination of destructive harvest, allometry, and remotes sensing. Before each experiment, destructive sampling of the forest floor and shrub layer was carried out in three 1 m^2 clip plots (Clark et al. 2015) at 12 plots within the burn unit. This destructive sampling technique was repeated after the fire (using an additional three clip plots per site), and consumption was estimated by comparing the measurements for several fuel classes. To measure canopy fuel loading before and after the experimental burns, ALS was flown before EX1, between EX1 and EX2, between EX2 and EX3, and following EX3. Using these data, canopy bulk density (CBD) was modeled, at a resolution of 10 m x 10 m x 1 m, from the surface up to maximum canopy height for each ALS acquisition. By integrating the CBD estimates and comparing pre- and post-fire values, a map of total consumption was generated for each burn. Cumulative distributions of canopy loading and consumption were generated by sampling values at a 1 m x 1 m resolution, effectively area-weighted by reducing the number of samples for pixels not wholly included in the respective regions of interest.

Fire environment measurements for each experiment were collected at three 12.5m tall overstory towers, equipped with two 3D sonic anemometers (Model 81000V, R.M. Young Co) and fine-wire thermocouples spaced 1.5m apart, which provided measurements of wind velocity, turbulence, and a vertical profile of air temperature. An additional tower was located outside of each block, to the west, in order to monitor the ambient conditions throughout the course of the fire (Figure 1). Tower locations within the block were selected so as to reduce any directional bias and clustering of measurements, allowing for flexible choice of an ignition line, given the conditions leading up to the burn. The choice of 12.5 m corresponded to roughly canopy height and is consistent with previous long-term flux studies carried out in the PNR. Sonic anemometers were also placed on the north and east roads for EX2 at 3 m (Figure 1), and sampling was carried out at 10 Hz by dataloggers (CR-1000 or CR-3000, Campbell Scientific). Infrequent gaps in the instantaneous anemometer data were filled via linear interpolation. Fuel moisture content (FMC) was measured from samples taken in adjacent blocks at the time of the experiments.

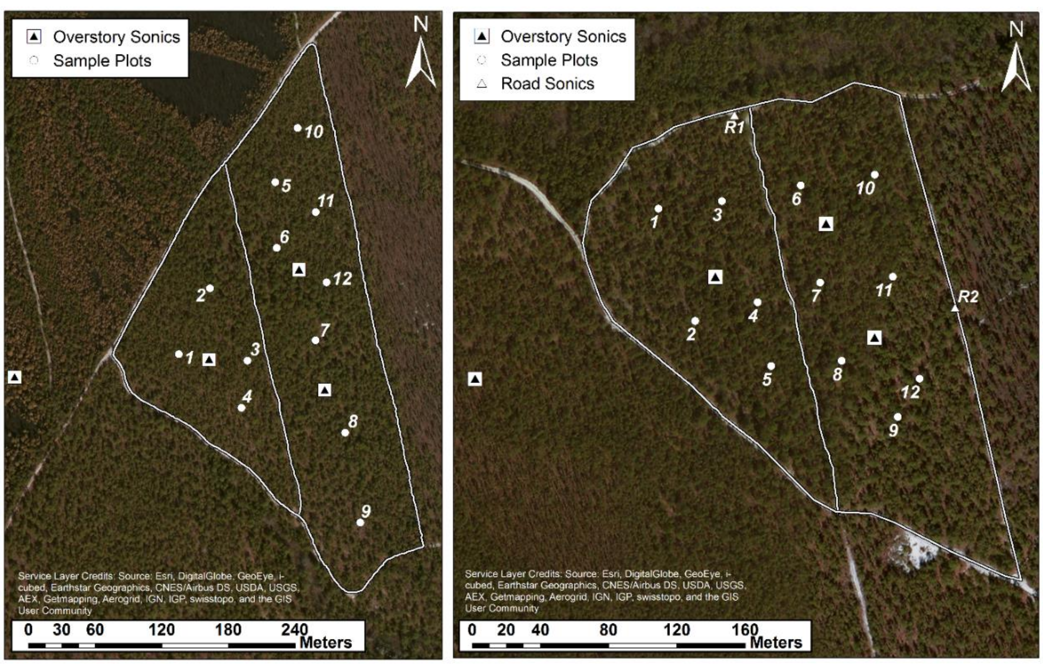

Figure 1 - Layout of the four overstory towers and 12 sampling site locations for the EX1 (left) and EX2 (right) burn blocks.

A time history of the fire progression was recorded from an aircraft using Rochester Institute of Technology's Wildfire Airborne Sensor Program (WASP) (McKeown et al. 2011). WASP provided time-stamped, othomosaiced, and georeferenced long-wave infrared (8.0-9.2 μm) and visible (0.4-0.9 μm) spectral band images, at a resolution of 640x512. Still images were obtained for each flyover of the aircraft at approximately three minute intervals (Figure 2).

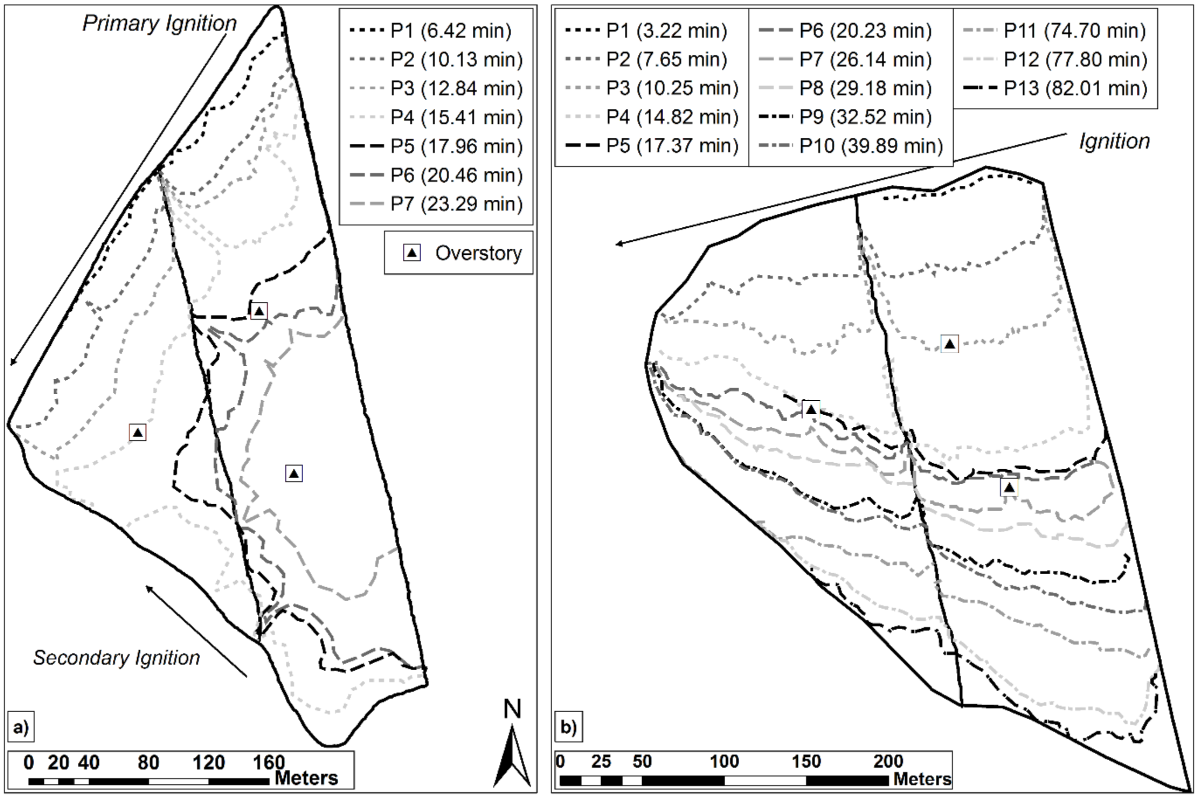

Figure 2 – IR-derived fire isochrones from (a) EX1 and (b) EX2, with time given in minutes from the start of ignition. Overstory towers are shown to help with spatial reference.

D. Model implementation

The initial simulations focus on a sub-section of interest from the full EX2 burn block, as shown in Figure 3. This choice was made in order to reduce run times and thus facilitate the study of a number of parameters that were not well defined experimentally, before progressing to larger scale simulations. The area encompassed by the numerical domain was 240 m x 225 m x 76.5 m. The horizontal grid resolution was 0.5 m x 0.5 m, while the vertical resolution was 0.5 m at ground level and, starting at a height of 2h (where h is canopy height), was stretched progressively to 1.5 m. A north wind was specified by a fixed velocity profile at the maximum y-boundary. The magnitude at canopy height was 3.9 ms^{-1} (following measured values), and a logarithmic profile was used above canopy and an exponential profile below. Ignition was carried out by the specification of a 'burner' with a fixed heat release rate for 20 seconds.

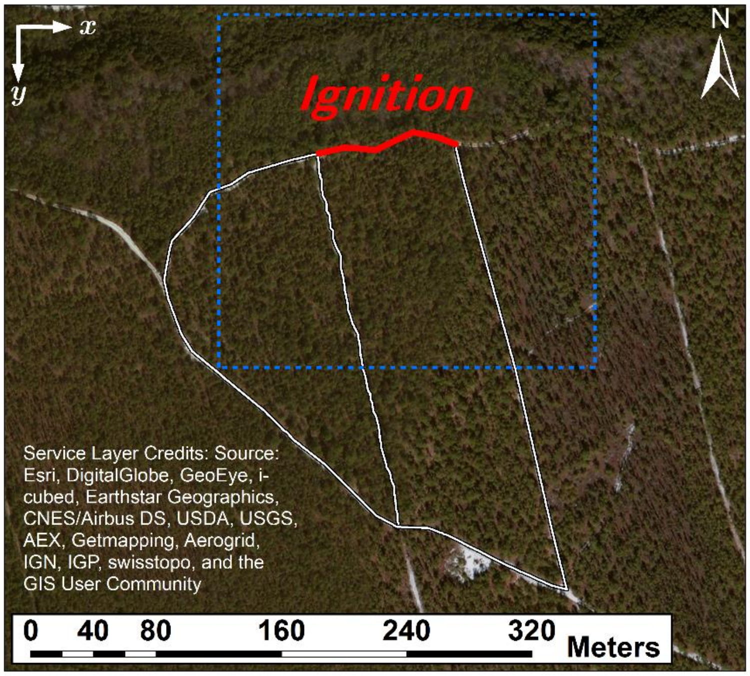

Figure 3 – Subset of EX2 burn block used to carry out parametric study of WFDS.

Fuel was subdivided into three main categories: (1) live needles in the canopy; (2) live 1-hr shrub fuel (which was further broken into three equal sub-classes of size); (3) dead needle litter. The canopy and shrub fuels were fully modeled within the 3D computational domain (Mell et al. 2009), while needle litter was treated as a boundary condition (owing to its height being much less than the grid dimensions) (Mell et al. 2007). Measurements from the field studies were used to direct the distribution of vegetation within the numerical domain, while thermophysical properties were based on a combination the aforementioned laboratory experimentation and values from literature.

As discussed above, implementation of WFDS was an important objective of the project. However, given the developmental state of the model for certain applications, and the large number of input parameters required, the main aim was to initialize the model and test its capabilities for simulating RxB activities against the experimental observations. Within this scope, a number of key parameters were identified, where uncertainty in the value (or even formulation) is significant, and model sensitivity was tested. Parameters tested included: (1) drag force in the raised fuel layers (shrub and canopy); (2) convective heat transfer coefficient in the litter layer; (3) the inclusion of smoldering combustion (vs. only flaming); (4) numerical resolution; and (5) fuel moisture content of all vegetation classes. Details are given in Table 1. While these by no means represent all the important parameters, they were identified as being potentially significant in affecting model predictions in our study. Following this study, simulations of post-burn conditions were attempted, with reductions in the loading and height of various vegetation layers based directly upon experimental measurements.

Table 1. Reference table of different parametric adjustments and the naming designation for the corresponding numerical simulation.

Simulation	Adjustment
S1	Baseline parameters
S2.X	Drag coefficient
S2.1	$0.5c_d$
S2.2	$1.5c_d$
S2.3	cylinder (Mueller et al. 2016)
S3.X	Surface convective coefficient
S3.1	h_c=cylinder (Bergman et al. 2007)
S3.2	$h_c=15\ W\cdot m^{-2}\cdot K^{-1}$
S4	Char oxidation
S5.X	Grid resolution
S5.1	Δx_i=0.33 m
S5.2	Δx_i=1.0 m
S6.X	Moisture content
S6.1	0.75M
S6.2	1.25M

IV. Key Findings

The key findings presented here are an abbreviated summary of the research that has been conducted as a part of this project. As our analyses and write-up of the datasets continues, and these data are integrated with follow-on projects, we expect to add significantly to this list.

A. Fuel Treatment Effects on Fuel Structure and Loading

Understory Fuels – The consumption of understory fuel components during prescribed burns were strong functions of initial loading in pitch pine/ scrub oak ecosystems (Figure 4; n = 8 RxBs; Clark et al. 2015). These relationships were not dependent on the intensity or ignition pattern of the fire and the relationships can thus be considered universal for the estimation of understory fuel consumption in this system.

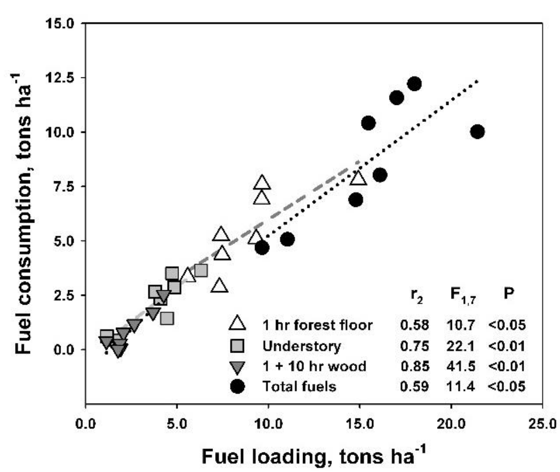

Figure 4. Surface and understory fuel loading and consumption estimated from 1.0 m^2 plots (n=10 to 32 in each burn) during eight prescribed burns in the New Jersey Pinelands.

Estimating canopy fuel consumption with LiDAR – The estimation of canopy fuel consumption is impossible using allometric techniques but this variable is a vital component in estimating fire severity, emissions, and resultant fuel loading. We collected point clouds pre- and post-prescribed fire using a plot-based terrestrial LiDAR, for which there were previously developed models of canopy bulk density (CBD; Clark et al. 2013) and an ALS. Figure 5 illustrates that this methodology provides a repeatable and accurate way to measure changes in canopy fuel loading and also CBD.

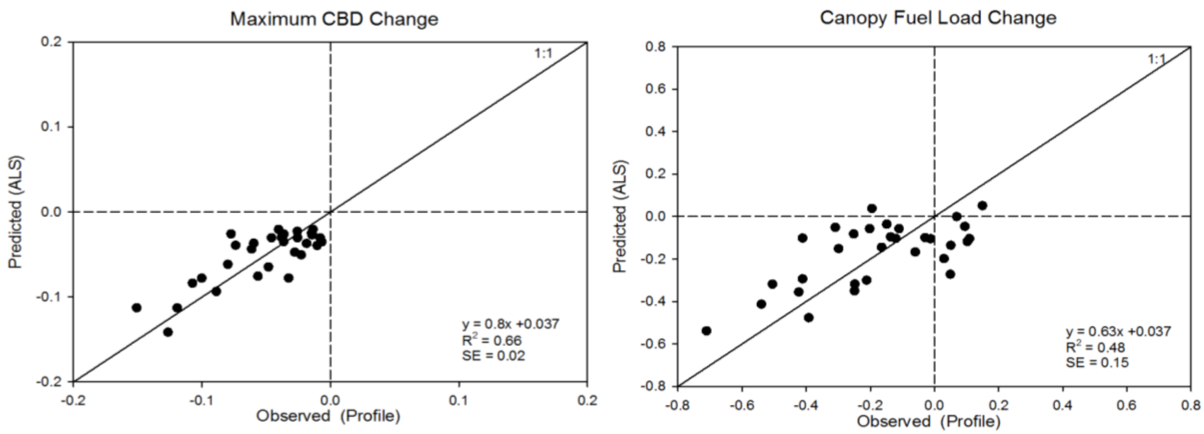

Figure 5. Scatters of fuel consumption predicted by ALS and ground-based LiDAR for 35 spatially coincident plots.

Prescribed fire history effects on canopy fuels – An analysis of prescribed fire history over a 20 year period indicates that there is more of an effect on canopy fuel loading from repeated burning than there is from a single, recent, prescribed burn. Table 2 illustrates this point clearly by showing a reduction of total canopy fuel loading by 7% for each additional prescribed fire within a burn unit with an r^2 of 0.99. Conversely, the time since a burn accounted for only a 4% reduction of canopy fuel load with much greater uncertainty in the model prediction (Table 1; r^2 = 0.3). Understory fuels (0-3m) are reduced more, and with more certainty, following repeated burning as well (Table 2). Finally, likely because of a combination of canopy consumption and a lack of recruitment into the canopy over time, the overstory (11-25 m) illustrates the largest difference with a 10% reduction of canopy with each additional burn vs. a 4% for time since fire. Again, repeated fires reduce the uncertainty of this effect (Table 2).

Table 2. Fuel load trajectory by analysis variable, canopy strata (m), regression coefficient, and model slope from landscape-scale stratification LiDAR derived canopy bulk density data categorized by burn history.

Analysis variable	Canopy strata	r^2	Slope (%)
Number of RxBs			
	Ladder (0-3m)	0.84	-13
	Mid (4-10m)	0.36	-4
	Overstory (11-25m)	0.84	-10
	Canopy Fuel Load (0-25m)	0.99	-7
Time since RxB			
	Ladder (0-3m)	0.30	-9
	Mid (4-10m)	0.93	-2
	Overstory (11-25m)	0.06	-3
	Canopy Fuel Load (0-25m)	0.13	-4

Contrasting canopy fuel loading following Prescribed Fire and Wildfire – This is one of the simpler, but perhaps most ecologically relevant, findings of our study. Our analysis of landscape-scale canopy bulk density profiles has shown the varying effects of prescribed fire and wildfire on canopy structure in the New Jersey Pinelands. Figure 6 shows that the average effect of a single prescribed fire reduces understory fuels while leading to an increase overstory fuels relative to unburned stands across the landscape. The mechanism for this increase in overstory loading is not clear, but is potentially related to changes in competitive interactions between overstory pines and understory shrubs, as well as pulsed nutrient release associated with pyromineralization of forest floor material that becomes available to overstory pines (Renninger et al. 2013, Carlo et al. 2016). In contrast, stands that have burned in a wildland fire once over the 20 year period had an increase in understory and a decrease in overstory fuels (Figure 6). This is most likely due to overstory mortality and subsequent understory recruitment.

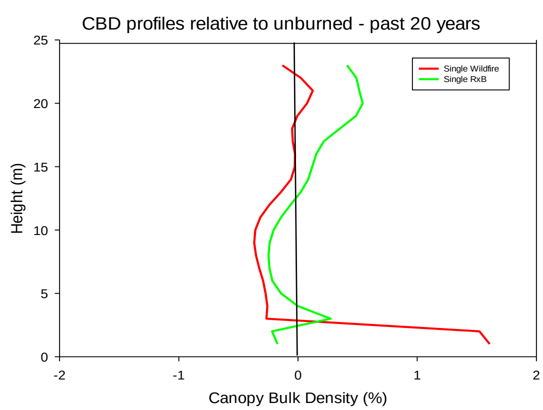

Figure 6. Canopy bulk density in 1 m height bins of stands burned in wildfire and prescribed fire once in the past 20 years relative to unburned stands.

B. Laboratory experimentation

Seasonal trends of the ignitibility and combustibility of live fuels – The purpose of this study was to analyze the flammability of live foliage over the course of a growing period and to determine any variation that can be attributed to the phenological state. The main conclusions of this work for dried needles were: 1) the flammability of growing and mature foliage is not necessary the same; (2) a combined factor (F_{total}), including ignitibility (time to ignition) and combustibility (peak heat release rate), for both the current cohort of needles and the cohort from the prior year, best describes the overall seasonal trends of flammability of canopy fuel; (3) Dried live foliar flammability does not correlate to the occurrence of a typical fire season in the NJ Pine Barrens, and (4) from a dry canopy fuel flammability stand point, August is the most dangerous month in which canopy involvement in fire behavior is at the highest risk (Thomas, *in prep)*.

The influence of fuel moisture content on the ignitibility and combustibility of live fuels – The purpose of this study was to explore the relationship of ignitability and combustibility to live fuel moisture of pitch pine needles. It was determined that moisture content significantly masks seasonal effects that were found for fully dehydrated foliage. Figure 7 presents a model and experimental data which illustrates a linear relationship between live fuel moisture content and ignition time given a fixed radiative heat flux for both first and second cohort needles. Peak heat release rate, however, does not follow a linear pattern (Figure 8) and is hypothesized to have three distinct zones on the curve where different mechanisms are dictating the response. Regime (1): Combustion intensity is driven by FMC and variation in plant chemistry. Regime (2): Combustion is independent of FMC and chemistry variation. Regime (3): Further reduction in combustion intensity due to FMC.

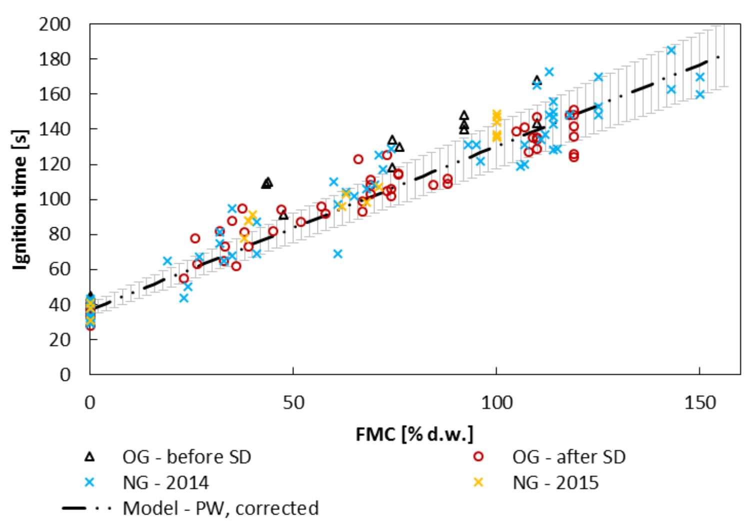

Figure 7. Time to ignition results (separated into time periods) for Pinus rigida live needles are compared to a corrected correlation. Error bars: 10% error margin.

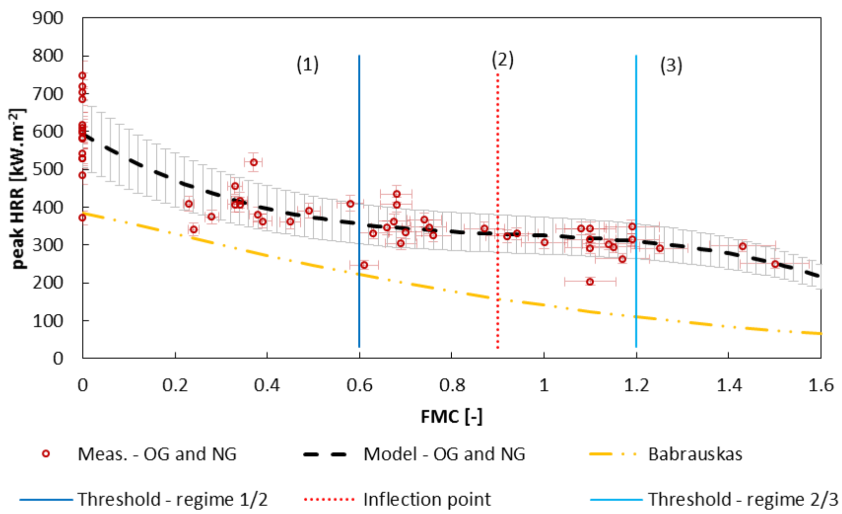

Figure 8. Measured and Predicted peak HRR with respect to FMC of all tests. "Babrauskas curve" (Babrauskas 2002; yellow "dashed-dotted" line). Error bars: Data: Standard deviation, Model: 15% error margin.

C. Field experimentation and evaluation

The objectives of this work were designed more to provide information for model evaluation than for experimentation. This limits the number of findings that are available to report. Here, we will present several observations that were consistent during EX1 and EX2, and contrasted with EX3.

The influence of fuels and wind on fire spread and intensity –

- Observations revealed predominantly surface fires, with localized torching of tree crowns, even though fires were lit with the wind.
- The involvement of canopy fuels in fire spread was identified with LiDAR measurements, and a clear transition from a pure surface fire was quantified in some locations. The variable consumption of canopy was captured well by the LiDAR data (Figure 9).

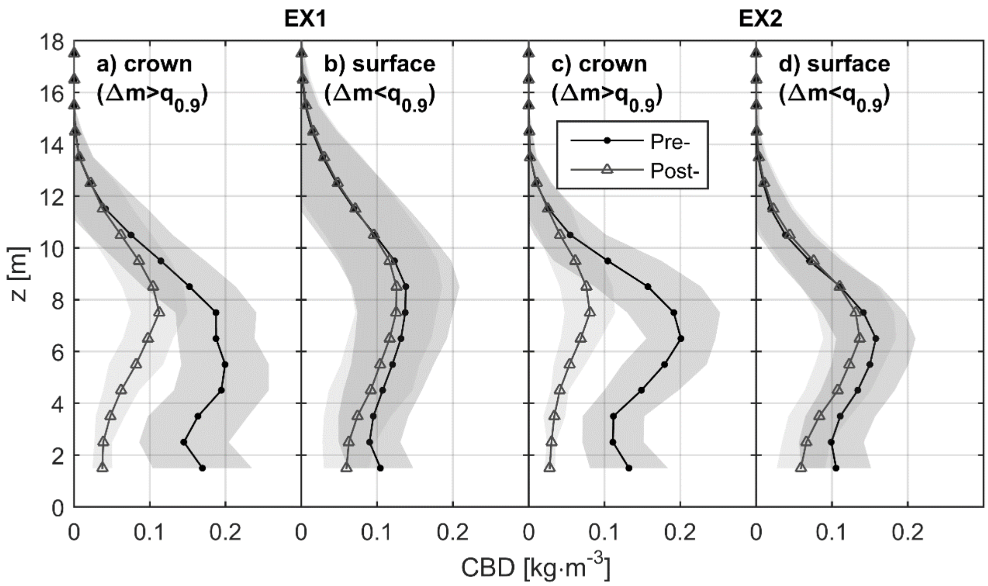

Figure 9 – Pre- (cricles) and post-fire (triangles) mean profiles of CBD for (a,b) EX1 and (c,d) EX2. (a,c) Profiles for areas of crowning are generated by averaging over all locations where canopy consumption values were above the 90th percentile, and (b,d) the remaining locations (mass consumption below the 90th percentile) are averaged to represent regions of surface fire.

- Ambient winds were relatively low. Wind is believed to have influenced low-intensity surface fire spread, and to have played a role in the aforementioned transition, but had little impact on more intense fire behavior.
- As the fire grew, local winds within the stand appeared to be dominated by fire induced flow, both preceding and following the passage of the fire front. The ratio of flame-height winds to overstory ambient winds was 4.3, and turbulent flow in the fire was dominated by horizontal turbulence.
- Embers played a major role in forward spread of these two fires, but were minimal in the lower intensity fire characterized by lower fuel loading.
- Because of the strong relationship between fuel loading and fuel consumption, fuel reduction was largely decoupled from above canopy heating and turbulence. In other words, low intensity fires such as Ex3 can significantly reduce surface fuels, but have little impact on ladder fuels.

D. Modeling

The baseline simulation with WFDS demonstrated a reasonable prediction of fire progression compared to the experimental data from the heading fire in EX2. A comparison of the advancing fireline for the simulation and experiment (Figure 10) shows a tendency for the simulation to match the more rapid periods of fire spread, with significant canopy involvement (P2-P4), but not the more subdued surface fire spread. Given that input vegetation properties were spatially heterogeneous in the horizontal directions, a quasi-steady behavior from the simulation is expected.

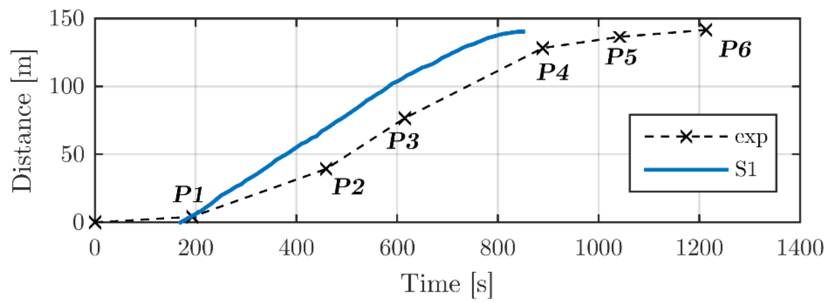

Figure 10 – Comparison of fireline progression for the experiment and baseline simulation (S1). Isochrone locations from the experiment labeled as in Figure 2b.

In terms of fuel reduction, the baseline simulation predicted 93% consumption in the litter layer and 90% consumption of fine fuel in the shrub layer. Comparatively, the EX2 measurements showed 74% and 76% consumption in the litter and shrub layer, respectively. The simulations also showed a considerable tendency to over-predict live needle canopy consumption, particularly in the lower layers of the canopy (Figure 11). These over-predictions are linked to the tendency for too rapid spread in the simulation compared to the periods of purely surface fire behavior in the experiment (Figure 12). This is, in turn, linked to uncertainty in model parameters.

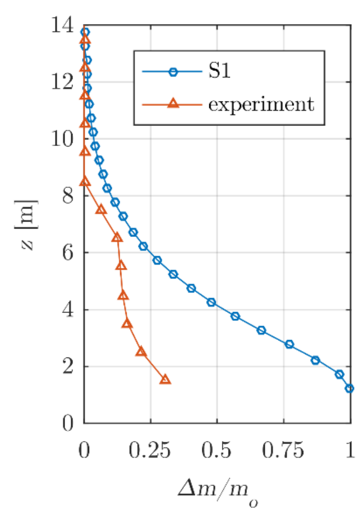

Figure 11 - Mean vertical profiles of percent live needle CBD consumption for the simulation (S1) and experiment.

The results of the parametric study revealed sensitivity to a number of parameters (Table 1). As an example, the change of predicted spread rate (normalized to the baseline value) is shown in Figure 12. Of the parameters, it was found that fuel moisture content had a potentially significant effect, along with the choice of drag coefficient in the raised fuel layer. The model chosen for convective heat transfer coefficient in the surface layer had a moderate effect, while the inclusion of char oxidation and adjustment of numerical resolution were relatively minor. While none of the adjustments lead to wholly unrealistic predictions, the clear demonstration of sensitivity gives guidence on where efforts must be focused if confidence in model predictions is to be improved. Additionally, efforts to model the post-burn, reduced fuel load simulations revealed a limitation of the model. For such a low intensity fire, the model tended not to predict any spread (depsite the third field experiment demonstrating spread could occur, albiet with very low intensity). Thus, while moderate to high intensity fires can be simulated with reasonable success, recreating either low intensity prescribed fire activities, or post-treatment wildfires (with significantly reduced fuel beds) will require further research efforts.

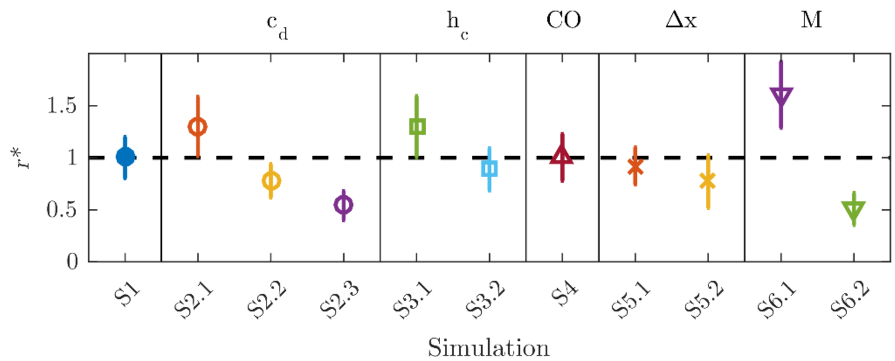

Figure 12 – Change in normalized spread rate for the different parameters (Table 1) investigated.

It should also be noted that the work performed during this project led directly to model development in two regions. The first is improvements in the ability to input fully three-dimensional heterogeneous fuel data over a large area (particularly from LiDAR-based raster data). The second is an advancement in the ability to specify turbulent wind boundary conditions with statistical features based on experimental measurement.

V. Management implications

The simplified objectives of this study were to: (1) explore the effect of fuel treatment activities on fuel structure and loading and then to (2) evaluate, in a modeling framework, the effectiveness of these treatments on fire spread and intensity. The management implications of our results in estimating fuel reduction and live fuel moisture effects on ignitability and combustibility will be discussed further here. However, much of our work in parameterizing, implementing, and simulating fires using WFDS is still “basic” or “foundational” research. WFDS has proven very useful in helping us to understand where knowledge gaps exist in: (1) our fundamental understanding of the physical fire environment, (2) our ability to parameterize the sub-models, and (3) methodologies to benchmark these models. However, when we attempted to implement the model for simulations of fire spread under the conditions of following fuel reduction treatments, the current version of the model was unable to adequately simulate fire spread to address this task. Therefore, much of this modeling work has little implication for fire management at this time.

Conversely, our findings in the realm of fuel treatment effects provide very actionable and useful information for both operational fire managers and those developing or justifying policy. Being able to estimate and bound the uncertainty of fuel consumption from prescribed burn operations are of great use for the justification of burning programs, the accurate estimation of smoke impacts using emissions factors, and the development of landscape-scale resource allocation plans. Our findings indicate the benefit of establishing and maintaining fuel treatments with multiple burns because of their increased effects on fuel reduction relative to the reduction found in single-entry burns. However, we have also found that in the NJ Pinelands, the prescribed burns are not mimicking the resultant forest structure that is typically found following the high-intensity crowning fires that may create critical habitat for the suite of endangered species which rely on open canopy. Leaving the overstory relatively intact may also limit the efficacy of prescribed burns under situations when fire weather is extreme and independent canopy fire is possible.

VI. Relationship to other recent findings and ongoing work in this topic

Members of our research team have developed several successful proposals and collaborations that build on the work that has been completed in this project.

- **Multi-scale analyses of wildland fire combustion processes in open-canopied forests using coupled and iteratively informed laboratory-, field-, and model-based approaches** – This work began as a proposal submitted by our team to the Department of Defense Strategic Environmental Research and Development Program (SERDP) which was fully funded. This project is based on improving our fundamental understanding of the physical processes that govern fire behavior to help improve physics-based fire spread models like WFDS. Much of the proposed work builds off of knowledge gaps that were identified in this project, particularly in the issues with simulating low-intensity fires. It is likely that two of the graduate students that worked on this project will perform their postdoctoral work on the SERDP project.
- **Measurement of firebrands generated during fires in pine-dominated ecosystems in relation to fire behavior and intensity –** This work was funded by JFSP and is a direct off-shoot of work that was completed during the field experimentation portion of this study. The focus is to understand how embers contribute to fire-front progression and also how ember production relates to structural ignition in the Wildland-Urban Interface. The new work is being conducted based on foundational work completed in this project. The research includes several team members and students from this project.
- **The Fire and Smoke Model Evaluation Experiment: Hierarchical 3D fuel and consumption maps to support physics-based fire modeling –** The Phase 1 FASMEE funds are dedicated to scoping and developing experimental designs and other requirements for the implementation of the FASMEE experiments (Phase 2). Several members of our team are involved with this process as either Co-Is or through consultations and are imparting fuel measurement methodologies, equipment design, and general advice about lessons learned. There is also potential for further integration using both FASMEE data and datasets from this study.
- **The physiology of pitch pine and long-term carbon storage in char following wildland fires –** Two research projects have capitalized on stands sampled during this JFSP project. The first has documented the effects of RxB treatments on photosynthesis and productivity of pitch pine, and quantified a fertilizer effect due to pyromineralization

leading to higher post-fire photosynthetic rates (USFS and Rutgers University). The second project is quantifying the long-term sequestration of carbon in charcoal in a soil environment where interactions with clays are nearly absent (upland soils in the PNR are > 92% sand; Rice University).

VII. Future work needed

There are a plethora of research questions that are still outstanding following this project. The effectiveness of a fuel treatment should be evaluated both in the changes to the physical environment (reduction of fuels) and also the resulting change in fire behavior. The scientific questions lie within our understanding of the physical fire environment, our ability to then adequately model fire spread and behavior without full understanding of physical processes, our ability to understand both the spatial and temporal efficacy of fuel reduction treatments as they relate to fire behavior or even ecology, and also the economic benefit of pursuing these treatments across a landscape.

The physical fire environment:

- How do the processes driving heat transfer, ignition, thermal degradation, flaming and smoldering combustion, mass consumption, and fire propagation at the scale of individual fuel particles and fuel layers affect fire behavior?
- How is fuel consumption affected by spatial variability in fuel particle type, fuel moisture status, bulk density, and horizontal and vertical arrangement of fuel components?
- How do multi-scale atmospheric dynamics, including ambient and fire- and forest overstory-induced turbulence, interact with the local fire environment to impact fire spread and convective and radiative heat transfer?

Fuels treatment effects on fuel loading:

- How could mechanical treatments and fire interact to change treatment longevity?
- What tools can be developed to help fire managers rate the effectiveness of a fuel treatment for assessment and reporting?
- How can fuel treatments better facilitate landscape-scale ecological goals?
- What are the long-term carbon accounting tradeoffs between a range of fuel treatments and wildfire exclusion?
- How can the spatial arrangements of fuel treatments on a landscape impact effectiveness?

VIII. Deliverables Crosswalk

Proposed	Delivered	Status
Dataset	LiDAR derived Fuel Map delivered to the NJFFS and NJANG.	Completed
Posters/presentations	See “Additional reporting” section	Completed – related documents posted on JFSP website
Refereed publication	See “Additional reporting” section	Completed – posted on JFSP website
Final Workshop	Because of travel limitations we supplanted the workshop with several webinars.	Completed
Ph.D. dissertation	Mueller’s Ph.D. dissertation.	In progress anticipated for fall of 2016

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Graduate Education

Gallagher, Michael. Rutgers, The State University of New Jersey. Anticipated spring of 2017.

Mueller, Eric. The University of Edinburgh. Anticipated fall of 2016.

Thomas, Jan Christian. The University of Edinburgh. Anticipated fall of 2016.