EXECUTIVE SUMMARY

Using a Computational Fluid Dynamic Model to Guide Wildland Fire Management

ESTCP Project RC-201303

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ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
ATV	All-terrain vehicle
CFD	Computational fluid-dynamics
DOD	U.S. Department of Defense
ESTCP	Environmental Strategic Technology Certification Program
LANL	Los Alamos National Lab
PDE	Partial differential equations
PFTC	Prescribed Fire Training Center
PI	Principal Investigator
RxCADRE	Prescribed Fire Combustion Atmospheric Dynamics Research Experiment

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1.0 INTRODUCTION

This research project was funded in 2012 by the Environment Security Technology Certification Program (ESTCP) to explore and verify the ability of FIRETEC, a physics-based wildland fire model coupled to a computational fluid-dynamics (CFD) model, to simulate fire behavior for various prescribed fire ignition patterns in longleaf pine sandhill fuel beds. Unlike FIRETEC and other physics-based models, current commonly used fire behavior models, e.g., FARSITE, BehavePlus, FSPro, etc. were designed to model spread from a single ignition point and are inadequate for predicting the complex influences of atmosphere, forest structure, and self-generating fire processes on wildland fire behavior. The project is a direct result of intense collaboration between fire scientists, fire modelers, and fire managers with a goal to co-produce research that is directly and immediately relevant to fire managers by using FIRETEC to explore managers' specific "burning questions." One of the more successful outcomes of the project was the creation of effective visual training aids for prescribed fire practitioners related to these specific field practitioner-generated questions.

2.0 OBJECTIVES

The specific performance objectives of the project were to (a) further validate FIRETEC's ability to simulate representative coupled fire/atmosphere behavior; (b) simulate prescribed fire behavior and phenomena in longleaf pine fuels on Eglin Air Force Base (AFB); and (c) use modeling results to enhance knowledge, skills, and abilities of fire practitioners nationally. The project was designed and managed using a co-production approach to demonstrate the potential to leverage the modeling power of a next generation fire spread model, FIRETEC, to improve wildland fire managers' knowledge base, situational awareness and prescribed fire outcomes, particularly as related to fire behavior dynamics associated with various fuel types, atmospheric conditions, and complex firing patterns by providing powerful visual training tools.

To meet objective (a), fuels and fire behavior data gathered from the Prescribed Fire Combustion Atmospheric Dynamics Research Experiment (RxCADRE) at Eglin Air Force Base (AFB) in Florida in 2012 were utilized as inputs for FIRETEC simulations in order to compare the simulations to a highly instrumented prescribed fire *in situ*.

Objective (b) involved running 46 different prescribed fire scenarios designed to establish baseline data and explore specific questions posed by managers, including: What is the effect of distance between ignition points on fire intensity and plume lofting? How does spot ignition moderate fire intensity as compared to "dash" or "line" ignition patterns? How do lighting unit boundaries affect fire behavior/effects in the burn unit? What is the effect of ignition point orientation (in-line vs. staggered) with regard to wind direction? How does forest structure affect wind fields and resulting fire behavior with various ignition patterns? How do the effects of the above ignition patterns change under varying wind conditions?

In order to meet objective (c), there was intense focus by the involved managers to ensure a project design that generated data and specific simulations that specifically addressed managers' "burning questions." Additionally, an extensive outreach strategy aimed towards prescribed fire practitioners and trainers was developed in order to share and to formally evaluate project results.

3.0 TECHNOLOGY DESCRIPTION

FIRETEC is an R&D100-winning (Linn et al. 2003), physics-based, three-dimensional computer code designed to capture what is a constantly changing, *interactive* relationship between wildland fire and its environment. As depicted in **Figure 1E**, during a FIRETEC wildland fire simulation, heat is produced, fuel (vegetation) and oxygen are reduced, and the surrounding air becomes buoyant, causing hot air to rise quickly above the fire and draw cooler air in near the base of the fire. Buoyant rise and related indrafts are mechanisms through which local combustion affects other areas of fires by changing the larger-scale flow patterns. Heat is exchanged between vegetation and gases as air moves through plants by convective heat exchange, and thermal radiation is emitted and absorbed by hot gases and vegetation. Moreover, vegetation imposes aerodynamic drag on airflow in relation to the bulk properties of the fuel bed.

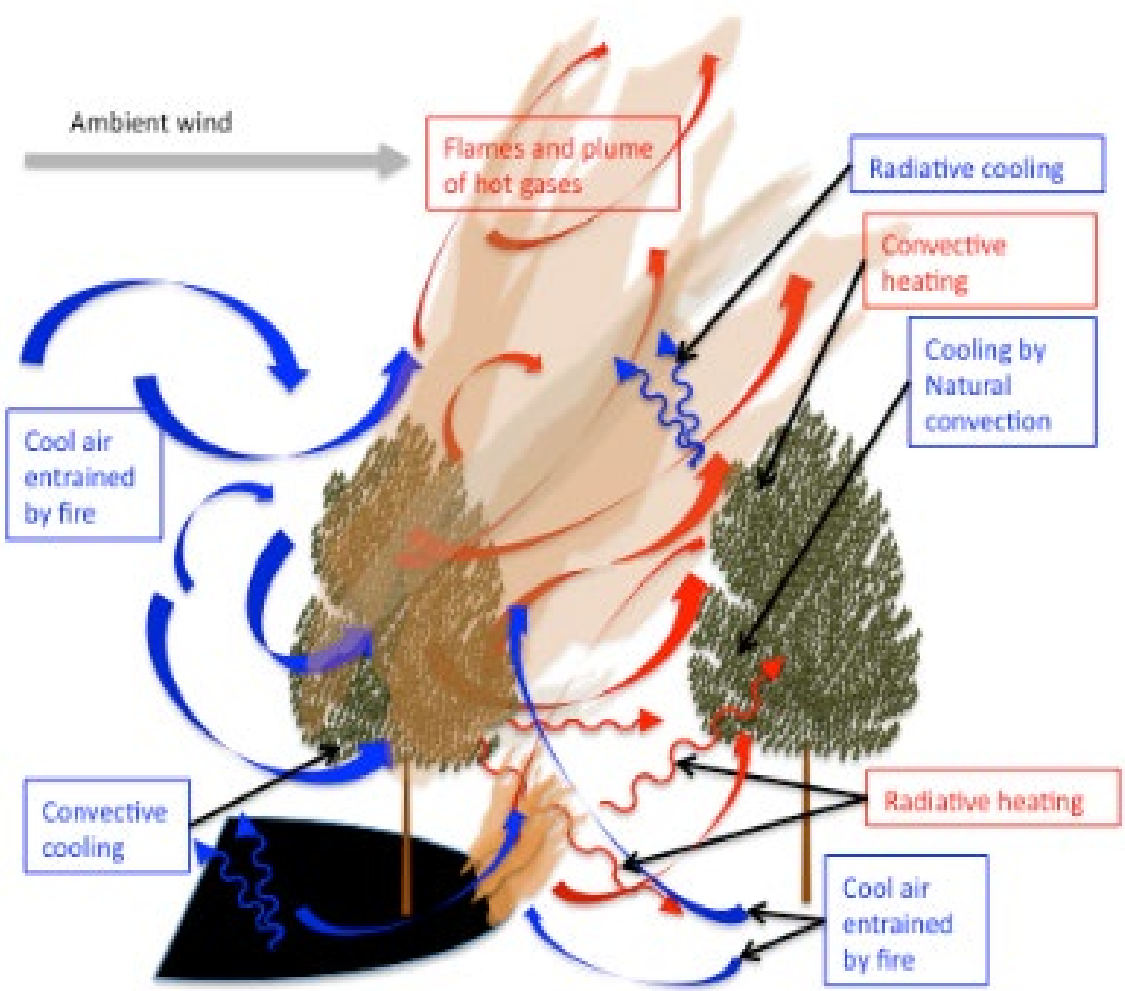

Figure 1E. FIRETEC Interactive Physical Processes

To accurately represent such interactive fire processes, FIRETEC combines physics models that represent combustion, heat transfer, aerodynamic drag and turbulence with a CFD model, HIGRAD, which represents airflow and its adjustments to terrain, vegetative obstructions, and the fire itself.

FIRETEC simulates the dynamic processes that occur within a fire and the way those processes influence each other (Linn et al. 2002) by solving a set of coupled partial differential equations (PDEs) for the conservation of mass, momentum, energy, chemical species, and turbulence (Linn 1997, Pimont et al. 2009, Smith et al. 2007, Clark et al. 2010, Dupuy et al. 2011). These equations describe the evolution in time and the variations in space of many physical properties that influence, or are influenced by, a fire, e.g., gas and vegetation temperatures, wind speed and direction, kinetic energy in the form of turbulence, oxygen concentrations, masses and characteristics of remaining vegetation, and other variables. These physical properties are computed as functions of time at millions of locations distributed in a three-dimensional terrain-following mesh that follows the simulated landscape.

4.0 PERFORMANCE ASSESSMENT

FIRETEC modeling results from this project are visually impressive, have proven very useful for enhancing knowledge of fire managers, and provide a significant step forward in FIRETEC validation efforts as related to complex prescribed fire simulations. Results from the Likert survey questions posed at the end of the workshops, and available in **Appendix A** , strongly support the value and utility of visual training aids produced through this demonstration.

In validating FIRETEC's ability to capture realistic coupled fire/atmosphere behavior, model performance success was based on the ability of FIRETEC to simulate fire-induced winds as well as radiative fluxes within one standard deviation of field values measured during RxCADRE campaigns at Eglin AFB. In the end, data from the 2012 RxCADRE S5 burn, which was approximately two hectares in size, were used to assess this performance objective. The quantitative success criteria that simulated fire-induced updrafts, ambient winds, and radiative fluxes will be within one standard deviation of values measured was partially met. The method for meeting the objective was reversed in a sense by demonstrating that the measured radiative flux and spread are within the distribution of the modeled results. The second success criteria, that modeled fire perimeters accelerate and decelerate directionally and temporally as expected in response to wind shifts measured in RxCADRE, was met. Innovative methodologies for measuring this model performance and comprehensive information regarding the processing of wind, fuels, and fire behavior data for this objective are included in **Section 5.2** and **Section 6.1** of the Final Report. Information on the perimeter, orientation, anemometer locations, and firing pattern for S5 are illustrated in **Figure 2E**. **Figure 3E** provides side-by-side comparison of S5 burn and FIRETEC simulation using nearest neighbor algorithm for wind inputs from the eight anemometers shown in the blue circles in **Figure 2E** (data from anemometers with red circles were determined to be flawed).

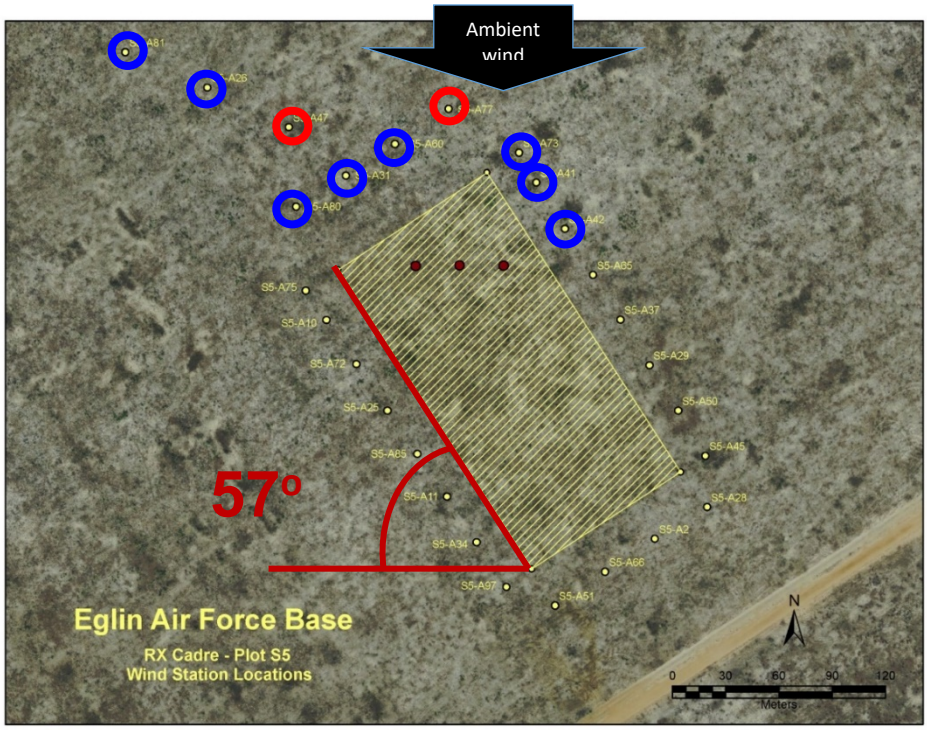

Figure 2E. Layout of the S5 Plot Anemometers

Layout of the S5 plot (hashed area) with 27 anemometers depicted as yellow numbered dots. The blue and red circles indicate the anemometers that were considered upwind in the context of ambient wind on the day of the burn. The three red dots indicate the center point and ends of the ignition line.

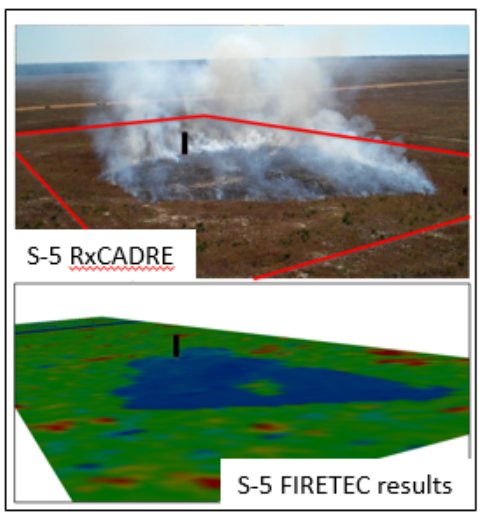

Figure 3E. Comparison of S5 FIRETEC Simulation to Actual Burn at 320 Seconds after Ignition

S5 burn from RxCADRE (top) and FIRETEC simulation, both at 320 seconds after ignition. The red lines in the top image show the extent of the FIRETEC computational grid. The black marker in the center of each image marks the location of an instrument tower. The large blue area in the bottom image indicates the modeled burn area. The other colors represent different vegetation types present, generated from a combination of field sampling and high resolution imagery analysis.

Direct conclusions:

- FIRETEC spread predictions were appropriate in direction and magnitude;
- FIRETEC spread patterns for RxCADRE S5 plot burns were heavily influenced by the details of the prescribed boundary conditions; and
- Validation of coupled fire/atmosphere model using standard statistical validation methodology for the RxCADRE 2012 S5 burn might be impossible because there are too many degrees of freedom in the specification of the environment.

Secondary lessons learned:

- Sparse fuels, high humidity, and light winds produced marginal burning conditions in which small changes in environment can have large changes in fire behavior, thus more detailed data is needed;
- Predictability of fire behavior depends on the relative magnitude of the ambient spread drivers compared to the fluctuations in these drivers (i.e., mean flow vs. turbulence fluctuations); and
- Models should be used more extensively in the design of future fire experiments in order to improve understanding of the data adequacy.

While it was discovered during the project that there were insufficient data available from the RxCADRE experimental burns at Eglin AFB to complete the statistical validation of model performance as specifically described for objective (a), a novel modified statistical approach was successfully applied to evaluate model performance, and the results of this analysis, as well as lessons learned from attempts to use RxCADRE data for model evaluation, provide significant value and insights into physics-based fire behavior modeling requirements.

Given the inherent difficulties related to standard statistical validation methods for fire behavior models, discussed in more detail under "Implementation Issues" below, the subject matter expertise of experienced prescribed fire managers was used as one evaluation criteria for measuring project success, particularly with regard to objectives (b) and (c). Specifically, a series of prescribed fire practitioner workshops were designed and carried out to present and formally evaluate project results. Likert survey questions were purposely designed to utilize fire managers' expertise for evaluating the project's success in meeting its objectives. For example, one of the success criteria for meeting objective (b) was "*Greater than 70% of fire managers "agree" or "strongly agree" that FIRETEC simulations captured critical aspects of fire behavior and spread in model simulations as determined by Likert survey.*" Of the workshop attendees, 94% said they "agree" or "strongly agree" with the statement "General fire phenomenology (indrafts, convection, flaming front interactions, intensity based on firing pattern, etc.) are modeled well by FIRETEC for the prescribed fire scenarios simulated for this project." To evaluate managers' perception of FIRETEC simulations as potential training tools, they were asked to respond to the statement, "Current prescribed fire practitioner training could be improved using visual products, data and lessons learned from this FIRETEC project." Ninety-seven percent "agree" or "strongly agree" with this statement, with 69% strongly agreeing.

While the project represents a significant step forward for fire behavior modeling, perhaps the greatest single outcome has been the adoption of FIRETEC simulations and data from this project into the curriculum of the National Interagency Prescribed Fire Training Center (PFTC), the premier prescribed fire training program in the U.S. As part of this national curriculum it will positively impact training and prescribed fire outcomes for hundreds of fire practitioners in the coming years. Some of the project products that are proving effective as training tools are highlighted below, though for full impact the simulation "movie clips" should be viewed. Some of the earlier simulations are included in one of the project's webinars, SFE Webinar: Next Generation Fire Modeling for Advanced Wildland Fire Training, available at: https://www.youtube.com/watch?v=TOrkny2ILik&feature=youtu.be.

Consumption data for surface, midstory, and canopy fuels were analyzed and compared for all scenarios. Fire managers' generally accepted expectations, or "rules of thumb" for these prescribed fire ignition scenarios are well illustrated by these FIRETEC simulations in **Figure 4E** below:

- Higher winds produce greater consumption for comparable ignition scenarios.
- As more simultaneous strips of head fire are ignited, overall consumption increases.
- Fire intensity increases as fire ignited per unit area increases, e.g., point source vs. strip head fire.

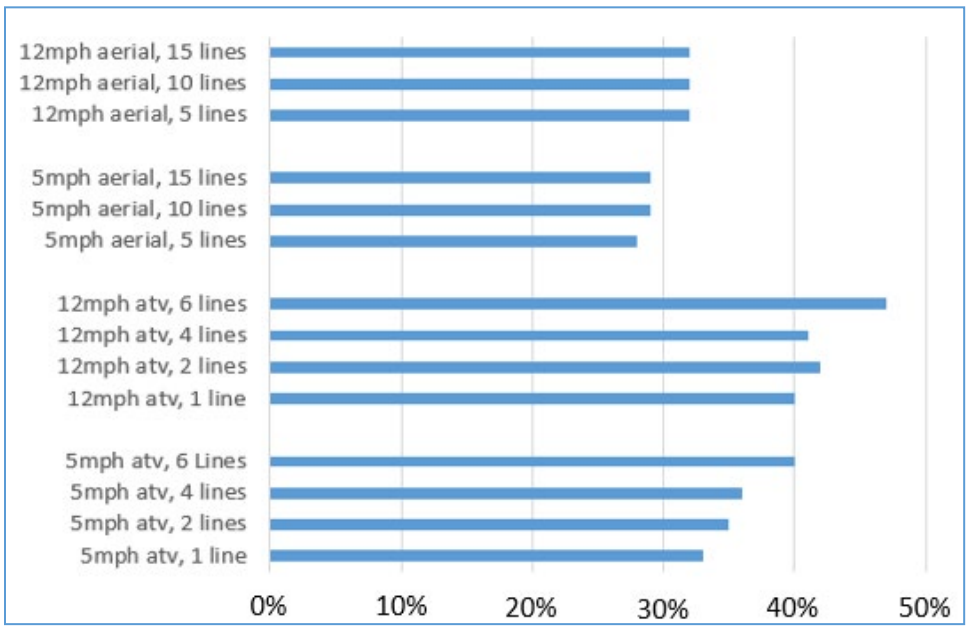

Figure 4E. Comparison of % Consumption for Combined Canopy/Midstory for 14 Scenarios

Comparison of % consumption for combined canopy/midstory for 14 scenarios including aerial point source and ATV strip ignition.

Comparisons of FIRETEC-generated rates of consumption for five-line all-terrain vehicle (ATV) strip ignition and aerial point source ignition at five mph and 12 mph winds also matched managers' expectation and are illustrated in **Figure 5E**. Specifically, for ATV strip ignition, ambient winds significantly impact rate of fuel consumption, and by extension fireline intensity, as illustrated by the differences in peak rates of consumption (~1750 vs. ~1250 kg/sec.) in the 12 mph versus five

mph wind scenarios. In keeping with managers' expectations, burnout times are noticeably faster with strip ignition when compared to aerial point source ignition, and for aerial ignition, wind speed impacts timing of consumption without a significant difference in peak rate of consumption.

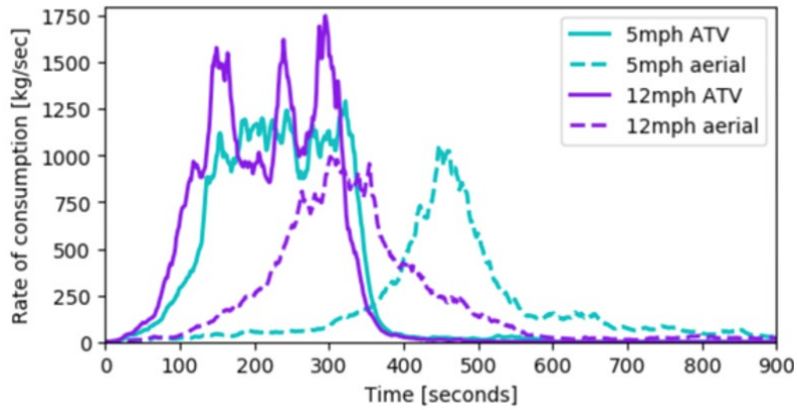

Figure 5E. Timing and Amount of Fuel Consumption for 5-line ATV/Strip Head Fire and Aerial Ignition

Timing and amount of fuel consumption for 5-line ATV/strip head fire and aerial ignition strategies.

The simulation associated with **Figure 6E** illustrates turbulence, plume rise, and rates of consumption comparing ATV strip head fire ignition with aerial point source ignition. "Trees" were removed for visual clarity.

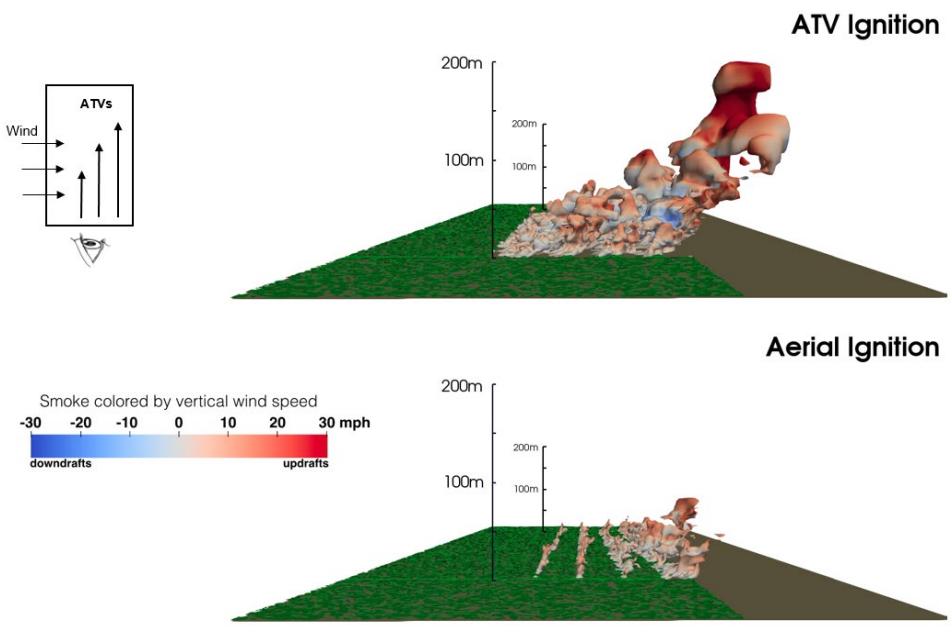

Figure 6E. Crosswind View Indicating Plume Height Three Minutes after Ignition Begins

Crosswind view indicating plume height three minutes after ignition begins with 12 mph wind comparing ATV strip head fire ignition with aerial point source ignition. Plume color denotes vertical wind speed of heated gasses.

Figure 7E shows a comparison of ignition line continuity (dot, short dash, long dash, and line) at a consistent 5-line ignition pattern. What is clear here is that ALL broken ignition patterns significantly reduce consumption (canopy + midstory) without interacting with winds (five or 12 mph), when compared to solid line ignition. The mean consumption shows a logarithmic increase in consumption proportional to the amount of ignition line that is continuous. This analysis suggests that for these wind speeds and a grid of five lines, any broken pattern results in significant moderation of fire behavior and thus consumption. In corroboration with fire managers' observations of discontinuous firing patterns, the power of convective cooling may be the dominating phenomenon driving consumption results in this analysis which included both canopy and midstory vegetation.

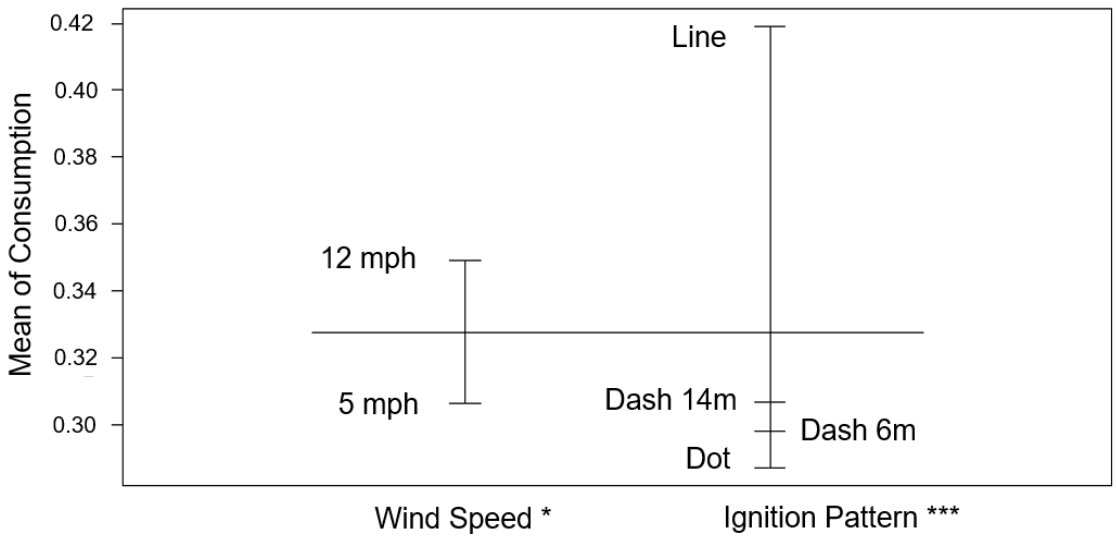

Figure 7E. Statistical Analysis of Combined Canopy and Midstory Consumption

*Statistical analysis of combined canopy and midstory consumption as related to wind speed and ignition pattern. * = P<.05, *** = P<.001*

Results from the project will be used to enhance not only future data collection methods and design for model validation efforts, but also prescribed fire outcomes through the use of FIRETEC simulations as powerful visual training tools for prescribed fire practitioners. FIRETEC simulations generated by this project are currently being utilized as training aids by the U.S. Department of Defense (DoD) as well as several state agencies and non-profits and, most importantly, as stated previously have been integrated into the curriculum of the National Interagency PFTC where they will aid in training the next generation of fire managers.

5.0 IMPLEMENTATION ISSUES

Standard statistical evaluation of fire behavior model performance based on replication is not plausible because no two fires are identical, i.e., they cannot be replicated. Even when ignition patterns, weather forecast, and plot layouts are similar for operational burns, differences in timing, strength, and directions of wind gusts, fuel arrangement, time of day, time of year, drought index and numerous other factors will produce different fire behavior and fire effects.

These same confounding factors preclude the use of standard statistical validation based on multiple replicates for fire models when comparing modeled outputs to actual fires. It was also discovered during attempts to simulate and compare RxCADRE small plot experimental burns that data gaps due to RxCADRE sampling design would make true model validation infeasible. Accordingly, other than the direct comparison of FIRETEC outputs to the RxCADRE S5 experimental burn, the focus of the FIRETEC simulations in this project was to explore the trends in phenomenology associated with various prescribed fire practices, not to predict exact spread rates, heat release, etc. for the various scenarios.

6.0 REFERENCES

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APPENDIX A WORKSHOP LIKERT SURVEY QUESTIONNAIRE

(Responses Highlighted)

FIRETEC 2018 Workshop Evaluation

1.

For each listed statement, check whether you:	Strongly Disagree	Disagree	Neither Agree or Disagree	Agree	Strongly Agree
a. General fire phenomenology (indrafts, convection, flaming front interactions, intensity based on firing pattern, etc.) are modeled well by FIRETEC for the prescribed fire scenarios simulated for this project.	☐1	☐	☐1	☐19	☐15
b. Current prescribed fire practitioner training could be improved using visual products, data and lessons learned from this FIRETEC project.	☐1	☐	☐	☐13	☐22
c. The FIRETEC model demonstration improved my understanding of prescribed fire ignition techniques and resulting fire behavior.	☐ 1	☐	☐3	☐ 23	☐ 3

2.

To what extent did the workshop today:	Not at all	A little	Some	Very Much
a. Increase your understanding of the new FIRETEC fire model?	☐	☐	☐11	☐25
b. Provide useful management information and strategies for addressing prescribed fire management questions?	☐	☐	☐ 23	☐ 13
c. Provide opportunities to collaborate with and learn from others in the fire management field?	☐	☐ 1	☐ 3	☐ 13
d. Cover topic(s) that address your fire and natural resource management information needs?	☐	☐ 3	☐ 8	☐ 6

3. **On a scale of 1 (definitely will not) to 10 (definitely will), how likely are you to use information from this workshop?**
Please circle your response: 1 2 3 4 5 6 (3) 7(3) 8(15) 9(5) 10(10) = 8.44 avg.

4. **Circle your primary fire-related role: Firefighter, Firing Boss, Burn Boss, Fire Program Manager/FMO, Fire Behavior Analyst, Fire Scientist/Researcher, Fire Ecologist, Modeler, Other _____**

5. **Do you have comments on how to make future workshops aimed at fire practitioners, more effective?**

THANK YOU FOR YOUR FEEDBACK AND FOR JOINING US TODAY!