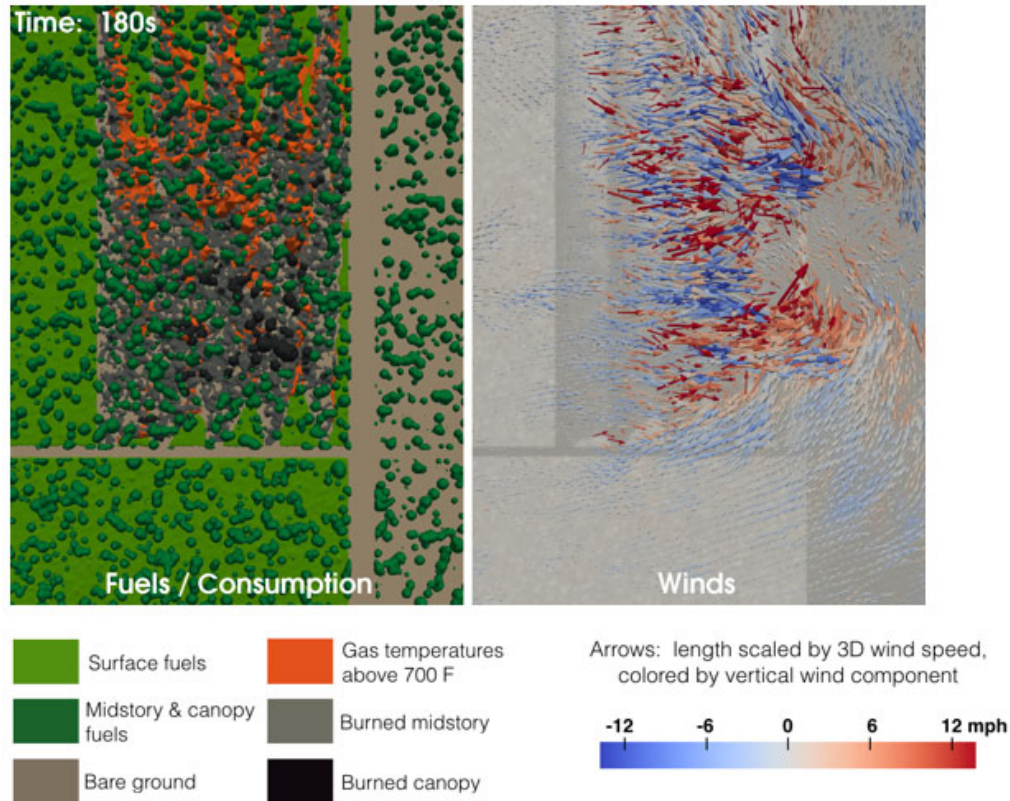




FINAL REPORT

ESTCP Project RC-201303 Using a Computational Fluid Dynamics Model To Guide Wildland Fire Management

PI: James H. Furman, *USDA Forest Service*

Co-PIs: Dr. Rodman R. Linn, *Los Alamos National Laboratory*

Brett W. Williams, *USAF Wildland Fire Branch*

Judith Winterkamp, *Los Alamos National Laboratory*

April 2019

REPORT DOCUMENTATION PAGE					<i>Form Approved OMB No. 0704-0188</i>													
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.																		
1. REPORT DATE (DD-MM-YYYY) 04/30/2019		2. REPORT TYPE ESTCP Final Report			3. DATES COVERED (From - To)													
4. TITLE AND SUBTITLE Using a Computational Fluid Dynamic Model to Guide Wildland Fire Management				5a. CONTRACT NUMBER														
				5b. GRANT NUMBER														
				5c. PROGRAM ELEMENT NUMBER														
6. AUTHOR(S) James Furman, Eglin Air Force Base, Natural Resource Section Dr. Rodman R. Linn and Judith Winterkamp Los Alamos National Laboratory Brett W. Williams, USAF Wildland Fire Branch				5d. PROJECT NUMBER RC-201303														
				5e. TASK NUMBER														
				5f. WORK UNIT NUMBER														
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Eglin Air Force Base, Natural Resource Section 151 John Sims Blvd. Valparaiso, FL 32580					8. PERFORMING ORGANIZATION REPORT NUMBER RC-201303													
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Environmental Security Technology Certification Program 4800 Mark Center Drive, Suite 17D03 Alexandria, VA 22350-3605					10. SPONSOR/MONITOR'S ACRONYM(S) ESTCP													
					11. SPONSOR/MONITOR'S REPORT NUMBER(S) RC-201303													
12. DISTRIBUTION/AVAILABILITY STATEMENT DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.																		
13. SUPPLEMENTARY NOTES																		
14. ABSTRACT 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 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.																		
15. SUBJECT TERMS Computational Fluid Dynamic Model, Wildland Fire Management, Atmosphere, Fire Behavior, Longleaf Pine Fuels																		
16. SECURITY CLASSIFICATION OF: <table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 33%; padding: 2px;">a. REPORT</td> <td style="width: 33%; padding: 2px;">b. ABSTRACT</td> <td style="width: 33%; padding: 2px;">c. THIS PAGE</td> </tr> <tr> <td style="text-align: center; padding: 2px;">UNCLASS</td> <td style="text-align: center; padding: 2px;">UNCLASS</td> <td style="text-align: center; padding: 2px;">UNCLASS</td> </tr> </table>			a. REPORT	b. ABSTRACT	c. THIS PAGE	UNCLASS	UNCLASS	UNCLASS	17. LIMITATION OF ABSTRACT UNCLASS		<table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 30%; padding: 2px;">18. NUMBER OF PAGES</td> <td style="padding: 2px;">19a. NAME OF RESPONSIBLE PERSON</td> </tr> <tr> <td style="text-align: center; padding: 2px;">99</td> <td style="padding: 2px;">James Furman</td> </tr> <tr> <td colspan="2" style="padding: 2px;"> 19b. TELEPHONE NUMBER (Include area code) 850-978-3236 </td> </tr> </table>		18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	99	James Furman	19b. TELEPHONE NUMBER (Include area code) 850-978-3236	
a. REPORT	b. ABSTRACT	c. THIS PAGE																
UNCLASS	UNCLASS	UNCLASS																
18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON																	
99	James Furman																	
19b. TELEPHONE NUMBER (Include area code) 850-978-3236																		

Acknowledgments:

In addition to the primary project team that includes Dr. Rodman Linn and Judith Wintercamp as key contributors from Los Alamos National Laboratory's Computational Earth Sciences Division and Brett Williams, Wildland Fire Manager at Eglin, AFB, the author would like to give special thanks to J. Kevin Hiers, Fire Scientist at Tall Timbers Research Station, without whom this project would probably never have taken place. Kevin's energy, enthusiasm and connections to the fire modeling and research world when he was serving as the Wildland Fire Program Manager at Eglin AFB were foundational for this project and a true testament to co-production between science and managers. Rod, Judy, Brett and Kevin all contributed substantially to the success of the project and to the writing and editing of this document. Special thanks also go to the Southern Fire Exchange, and Dr. David Godwin in particular who recognized the value and potential positive impacts of this project and played a significant role in assuring successful dissemination of project results to the wildland fire community. Army Installation Management Command and the Air Force Wildland Fire Branch also played a significant role by supporting staff time for the PI and a Co-PI for this project. Thanks also go to Dr. Alex Jonko from Los Alamos National Laboratory for her creativity, energy and responsiveness processing FIRETEC visualizations for workshops and this document. And finally, though there are too many names to list here, thanks to the research scientists and managers that made the RxCADRE experiments at Eglin AFB a successful reality. Data from RxCADRE played an important part in the success of this project.

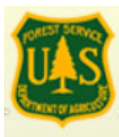


TABLE OF CONTENTS:

EXECUTIVE SUMMARY

OBJECTIVES OF THE DEMONSTRATION

TECHNOLOGY DESCRIPTION

DEMONSTRATION RESULTS

IMPLEMENTATION ISSUES

1.0 INTRODUCTION

1.1 BACKGROUND

1.2 OBJECTIVE OF THE DEMONSTRATION

1.3 REGULATORY DRIVERS

2.0 TECHNOLOGY/METHODOLOGY DESCRIPTION

2.1 TECHNOLOGY/METHODOLOGY OVERVIEW

2.2 TECHNOLOGY/METHODOLOGY DEVELOPMENT

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY/ METHODOLOGY

3.0 PERFORMANCE OBJECTIVES

3.1 Performance Objective 1

3.2 Performance Objective 2

3.3 Performance Objective 3

4.0 SITE DESCRIPTION

4.1 SITE LOCATION AND HISTORY

4.2 SITE CHARACTERISTICS

5.0 PROJECT DESIGN

5.1 CONCEPTUAL PROJECT DESIGN

5.1.1 Model Comparison with RxCADRE Fire

5.1.2 Baseline Fire Scenarios

5.1.3 Fire Phenomenology Study

5.1.3.1 Alignment of spot ignitions-

5.1.3.2 Impact of dash fire ignition

5.1.3.3 Impact of open midstory

5.1.3.4 Impact of venting at flanks

5.1.4 FIRETEC Baseline and Phenomenology Study Parameters

5.1.4.1 Dimensions

5.1.4.2 Fuels

5.1.4.3 Weather

5.1.4.4 Ignition Patterns

5.1.4.5 “Containing” the Fires

5.1.5 Additional Completed Simulations

5.1.5.1 Increased aerial ignition point density

5.1.5.2 “High fuel moisture” in “Open midstory”

5.1.5.3 Increased midstory bulk density

5.1.5.4	“High fuel moisture” simulations with hardwood leaves on
5.2	BASELINE CHARACTERIZATION AND PREPARATION
5.2.1	RxCADRE S5 Winds Characterization
5.2.2	S5 Fuels Characterization
5.3	DESIGN AND LAYOUT OF TECHNOLOGY AND METHODOLOGY COMPONENTS
5.4	FIELD TESTING
5.5	SAMPLING PROTOCOL
5.6	SAMPLING RESULTS
6.0	PERFORMANCE ASSESSMENT
6.1	PERFORMANCE OBJECTIVE 1
6.1.1	Simulations
6.1.2	Radiative fluxes
6.2	PERFORMANCE OBJECTIVE 2
6.2.1	FIRETEC Sensitivity to Variations in Fuel Bulk Density/Loading and Live Fuel Moisture
6.2.2	Sensitivity of FIRETEC to Changes in Firing Patterns and Environmental Factors as Illustrated by % Consumption
6.3	PERFORMANCE OBJECTIVE 3.
7.0	COST ASSESSMENT
7.1	COST MODEL
7.2	COST DRIVERS
7.3	COST ANALYSIS AND COMPARISON
8.0	IMPLEMENTATION ISSUES
9.0	REFERENCES

Appendix A: Points of Contact

Appendix B: General Fuel Descriptions

Appendix C: Estimating Fire Effects: Relative Consumption

Appendix D: Expert Intuition Likert Survey Questions

LIST OF FIGURES

- 1E. FIRETEC interactive physical processes
- 2E. Layout of the S5 plot anemometers
- 3E. Comparison of S5 FIRETEC simulation to actual burn at 320 seconds after ignition
- 4E. Comparison of % consumption for combined canopy/midstory for 14 scenarios
- 5E. Timing and amount of fuel consumption for 5-line ATV/strip head fire and aerial ignition
- 6E. Crosswind view indicating plume height three minutes after ignition begins
- 7E. Statistical analysis of combined canopy and midstory consumption as related to wind speed and ignition pattern
1. FIRETEC interactive physical processes
2. 3-D computational grid representation
3. International Crown Fire Modeling Experiment showing FIRETEC results
4. Modeling interactions between lines of fire
5. Map of Eglin AFB

6. General Project Schematic
7. Schematic of 18 baseline FIRETEC simulations
8. Schematic of prescribed fire phenomenology study simulations
9. Computational domain dimensions
10. Additional completed simulations
11. Layout of the S5 plot anemometers
12. Wind speed and direction for 10 upwind anemometers
13. Fuel class verification
14. Fuel classification field sampling
15. Flow chart for processing of the raw 0.15 m imagery through fuels mapping
16. Similar process for modeling fuel moisture and fuel height
17. RxCADRE 2008, 2011, and 2012 burn unit locations at Eglin AFB, FL
18. Location of S5 in relation to other RxCADRE 2012 burn units
19. FIRETEC computation grid used for S5 simulations
20. Fire perimeters from FIRETEC simulations at 320s after ignition initialized with wind series from individual anemometers
21. Fire perimeters from FIRETEC simulations at 320s after ignition initialized with averaged wind
22. Spread rates plotted as a function of simulation specific wind speed
23. Combined Images of S5 burn from overhead drone and boom-mounted FLIR
24. Comparison of S5 FIRETEC simulation to actual burn at 320 seconds after ignition
25. Shape comparison between S5 burn and FIRETEC simulation
26. Location of points used for upward radiative flux comparisons
27. Measured upward flux as related to time since rapid heating began
28. Comparison between simulated and measured peak vertical radiative heat fluxes
29. Baseline fire scenarios modeled with FIRETEC
30. Five-line ignition Fire Phenomenology Study
31. View from upwind illustrating differences in modeled maximum plume heights between ATV and aerial point source ignitions
32. Crosswind view with plume height three minutes after ignition begins
33. Visual consumption comparison with increased fuel loading, midstory, low fuel moisture and 12 mph wind
34. Visual consumption comparison with increased fuel loading, open midstory, high fuel moisture and 12 mph wind
35. Visual consumption comparison with increased fuel loading, midstory, low fuel moisture and 5 mph wind
36. Visual consumption comparison with increased fuel loading, open midstory, high fuel moisture and 5 mph wind
37. Visual consumption comparison with increased fuel loading, using aerial point source ignition with midstory, low fuel moisture and 12 mph wind
38. Visual consumption comparison with increased fuel loading, using aerial point source ignition with open midstory, high fuel moisture and 12 mph wind

39. Comparison of % consumption for combined canopy/midstory for 14 baseline scenarios described in Figure 7.
40. Consumption comparisons between 5-line strip head fire ignitions with open midstory/high fuel moisture and standard/dry fuel conditions.
41. Canopy consumption comparison for different 5-line firing techniques under 5 mph and 12 mph winds with identical fuels
42. Spatial statistical analysis of combined canopy and midstory consumption (%) for wind speed, number of ignition lines and ignition type using 3-Way ANOVA.
43. Statistical analysis of combined canopy and midstory consumption as related to wind speed and ignition pattern.
44. Statistical analysis of midstory consumption as related to wind speed and ignition type interaction.
45. Timing and amount of fuel consumption for ATV/strip head fire and aerial point source ignition. strategies.
46. 5-line ATV ignition with 5 mph winds displayed in “forest fire” context with “smoke” removed on left and as vertical wind vectors on right.
47. 5-line ATV ignition with 5mph winds; focus on winds through a vertical slice

LIST OF TABLES

Table 1. Performance Objectives

Table 2. Statistics from the 8 upwind anemometers from S5 burn unit that were used to initialize wind in the FIRETEC simulations

Table 3. Input parameters for 10 simulations of the S5 burn

Table 4. Spread rates for S5 simulations as well as wind speed and direction used to compute them

Table 5. Cost Model

LIST OF ACRONYMS

AF – Air Force

AFB – Air Force Base

AFSOC – Air Force Special Operations Command

AFWFB – Air Force Wildland Fire Branch

ATV – All terrain vehicle

CFD – Computational Fluid Dynamics

CSU-MAPS – California State University Mobile Atmospheric Profiling System

CULAR – Collaborative University of California/Los Alamos Research

DOD – Department of Defense

DODI – Department of Defense Instruction

ESTCP – Environmental Strategic Technology Certification Program

ETTC – Eglin Test and Training Complex

FDFM – Fine dead fuel moisture

FRAMES - Fire Research and Management Exchange System

GCPEP – Gulf Coastal Plain Ecosystem Partnership

ICFME - International Crown Fire Modeling Experiment
IMCOM – Installation Management Command
INRMP – Integrated Natural Resources Management Plan
INRA – Institut National pour la Recherche Agronomique
JFSP – Joint Fire Science Program
LANL – Los Alamos National Lab
LDRD – Los Alamos National Lab Directed Research and Development
MRTFB – Major Range and Test Facility Base
NAFRI – National Advanced Fire and Resource Institute
NASA - National Aeronautical and Space Agency
NAVSCLEOD – Navy Explosive Ordnance Disposal School
NFES – National Fire Equipment System
NIFC – National Interagency Fire Center
NWCG – National Wildfire Coordinating Group
PDE – Partial Differential Equations
PFTC – Prescribed Fire Training Center
POC – Point of Contact
RxCADRE – Prescribed Fire Combustion Atmospheric Dynamics Research Experiment
SERDP – Strategic Environmental Research and Development Program
TRAWING – Training Wing
TTA – Tactical Training Area
TW – Test Wing
UAS – Unmanned Aerial Systems
USDA – U.S. Department of Agriculture
USFS – U.S. Forest Service
WASP – Wide Angle Sensor Package

EXECUTIVE SUMMARY:

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 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.

OBJECTIVES OF THE DEMONSTRATION

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 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, FL 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 does 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.

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.

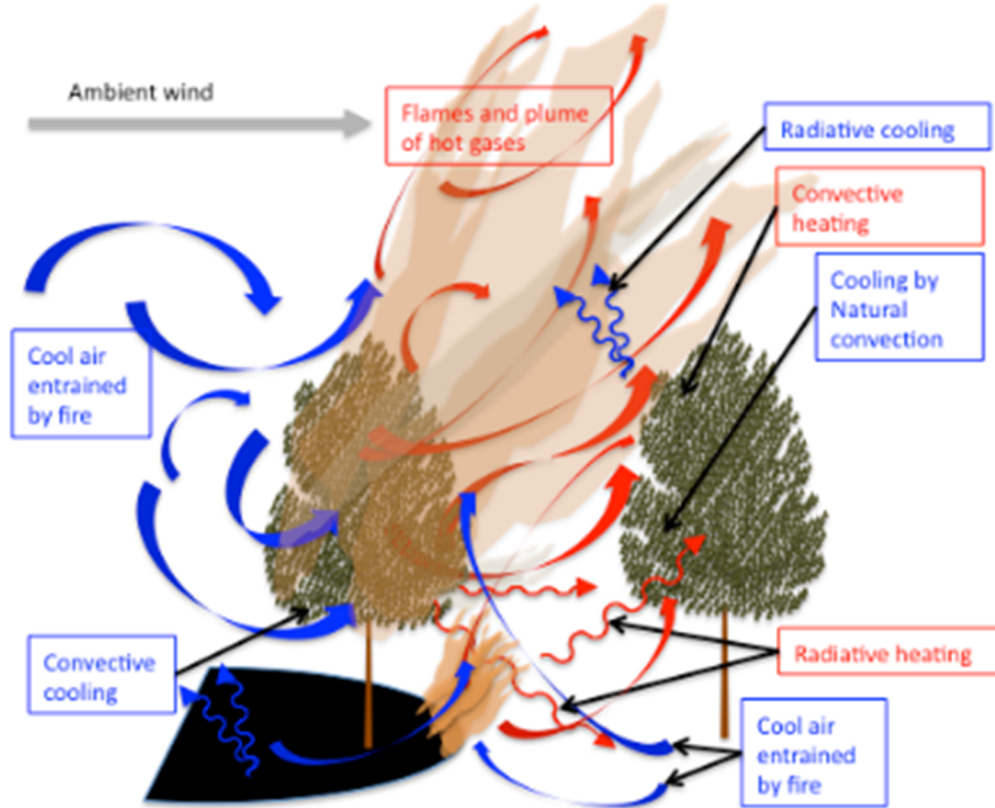


Fig. 1E. Multiple interactive physical processes are integrated in FIRETEC simulations.

To accurately represent such interactive fire processes, FIRETEC combines physics models that represent combustion, heat transfer, aerodynamic drag and turbulence with a computational fluid-dynamics (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.

DEMONSTRATION RESULTS

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 the appendix to this report, 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 2 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 Rx CADRE, 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 Sections 5.2 and 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 8 anemometers shown in the blue circles in Figure 2E (data from anemometers with red circles were determined to be flawed).

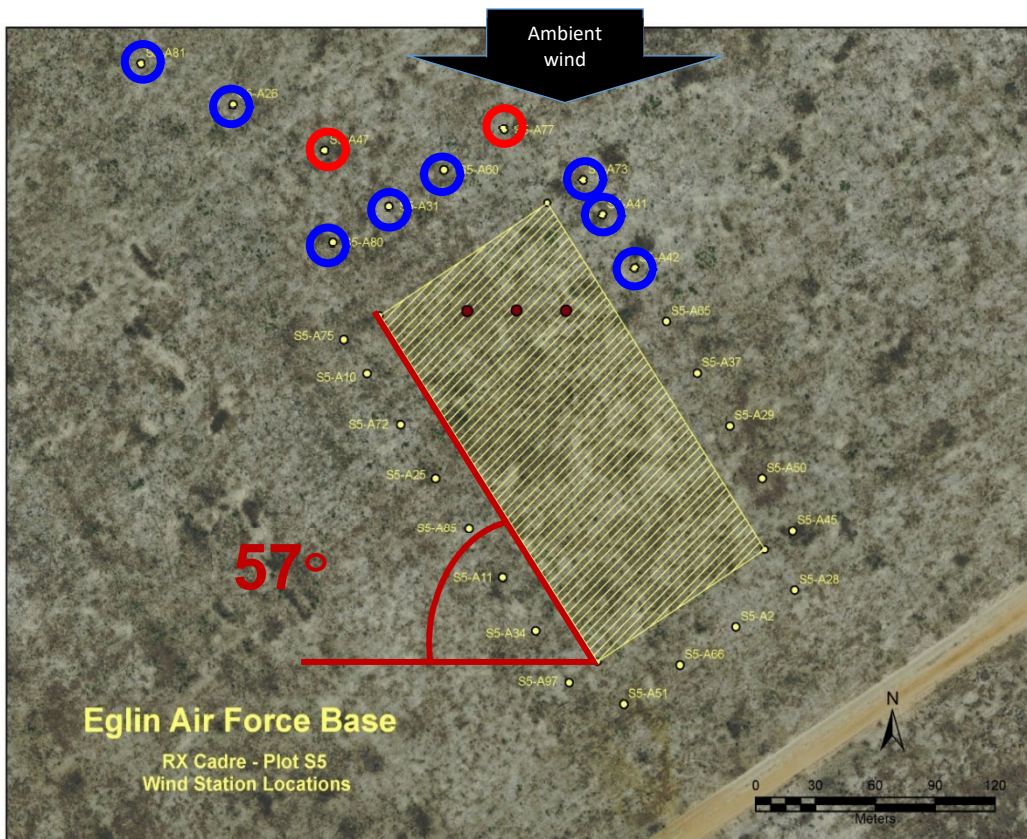


Fig. 2E. Layout of the S5 plot (hashed area) with 27 anemometers depicted as yellow numbered dots. The blue and red circles indicate the anemometers that were considered upwind in the context of ambient wind on the day of the burn. The three red dots indicate the center point and ends of the ignition line.

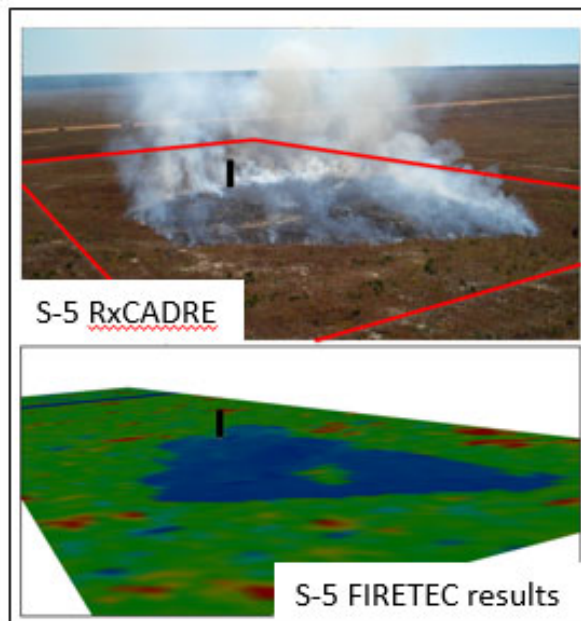


Fig. 3E. S5 burn from RxCADRE (top) and FIRETEC simulation, both at 320 seconds after ignition. The red lines in the top image show the extent of the FIRETEC computational grid. The black marker in the center of each image marks the location of an instrument tower. The large blue area in the bottom image 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
- 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)
- 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, 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 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.

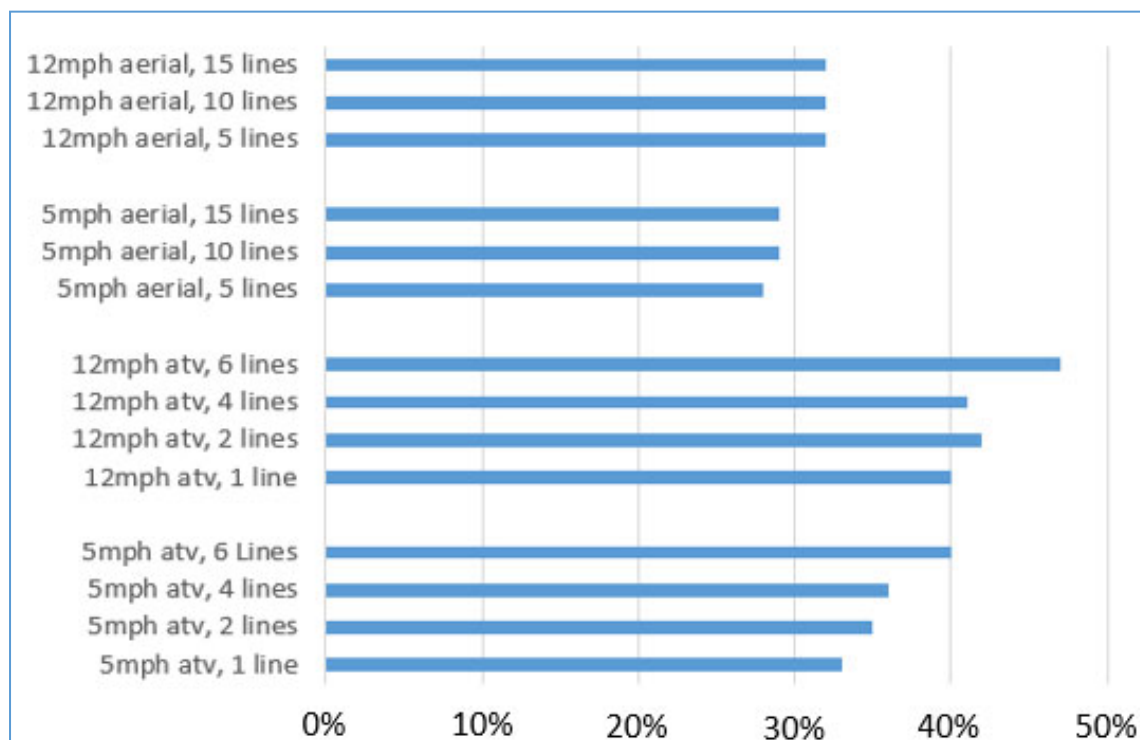


Fig. 4E. Comparison of % consumption for combined canopy/midstory for 14 scenarios including aerial point source and ATV strip ignition.

Comparisons of FIRETEC-generated rates of consumption for five-line ATV strip ignition and aerial point source ignition at 5 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 vs. 5 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.

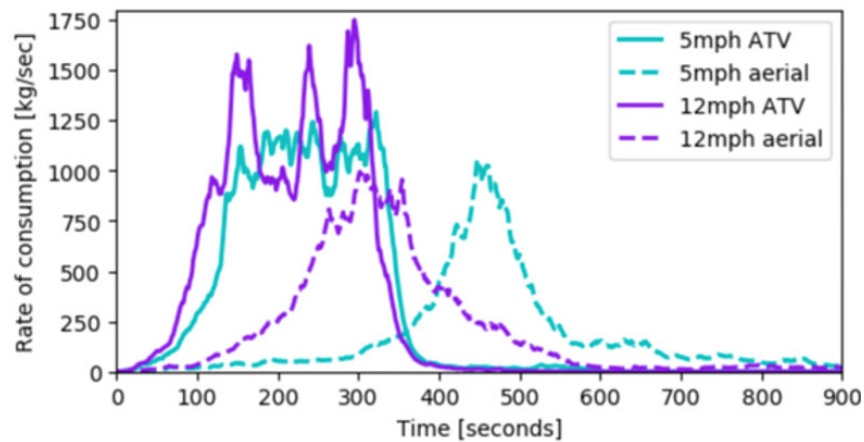


Fig. 5E. Timing and amount of fuel consumption for 5-line ATV/strip head fire and aerial ignition strategies.

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.

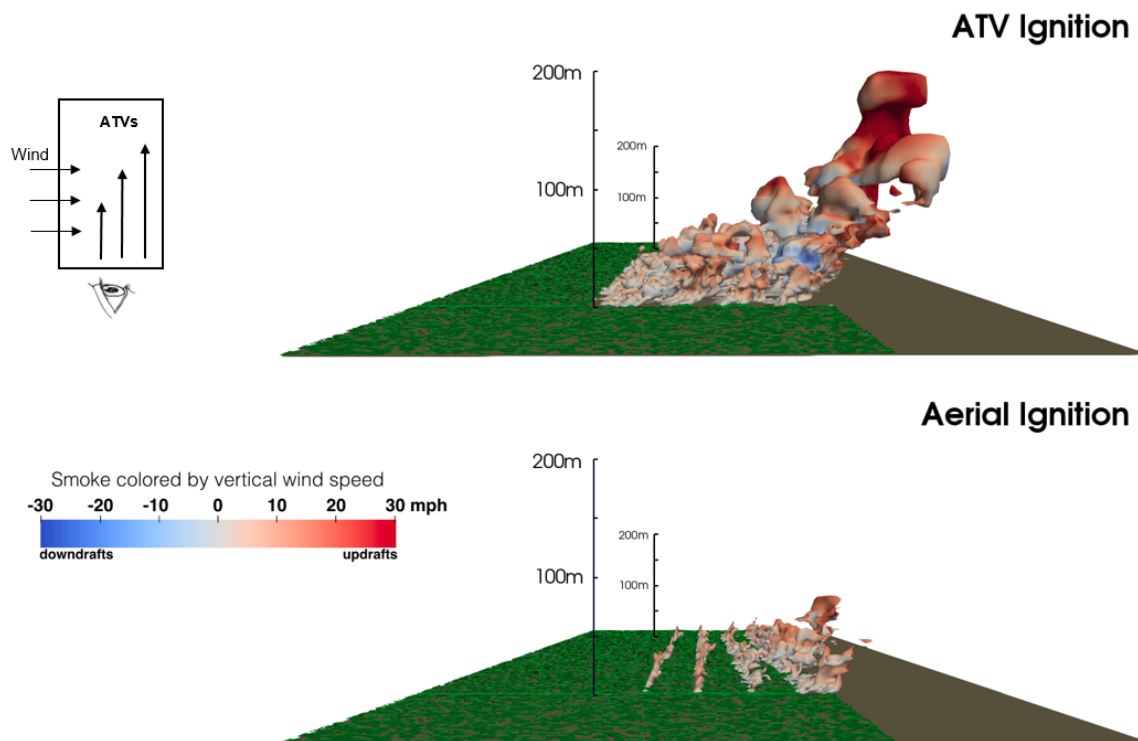


Fig. 6E. Crosswind view indicating plume height three minutes after ignition begins with 12 mph wind comparing ATV strip head fire ignition with aerial point source ignition. Plume color denotes vertical wind speed of heated gasses.

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 (5 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 5 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.

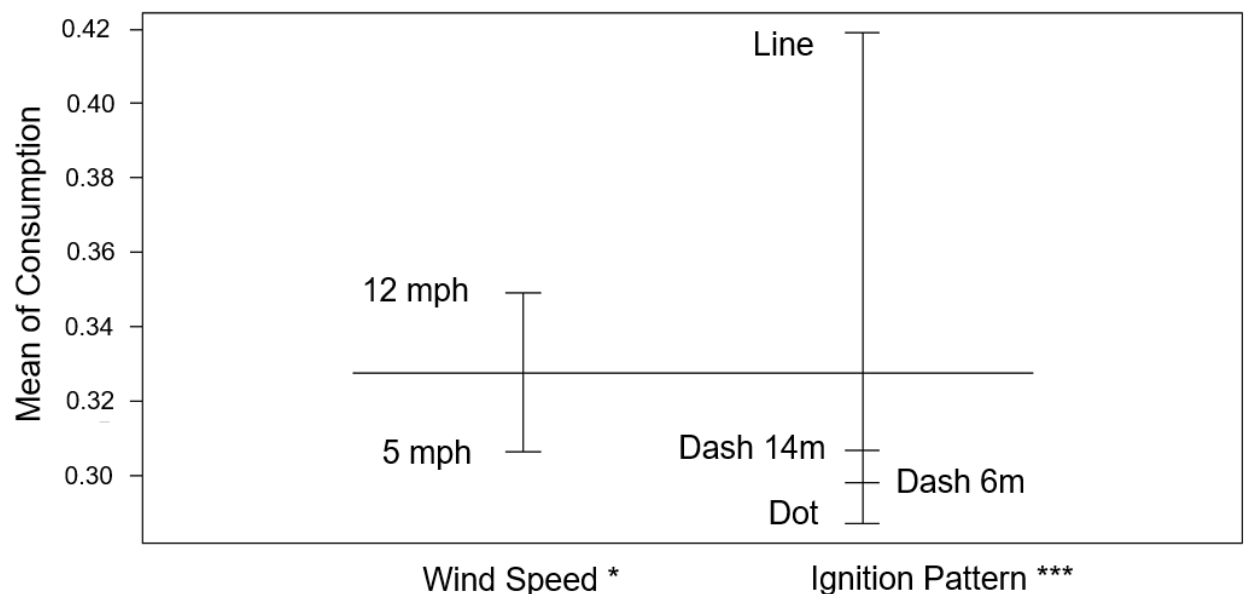


Fig. 7E. Statistical analysis of combined canopy and midstory consumption as related to wind speed and ignition pattern. * = $P < .05$, *** = $P < .001$

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 Department of Defense 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 Prescribed Fire Training Center where they will aid in training the next generation of fire managers.

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.

1.0 INTRODUCTION

This research project was funded in 2012 by the Environmental Security Technology Certification Program (ESTCP) to explore and verify the ability of FIRETEC, a computational fluid dynamics model developed at Los Alamos National Laboratory (LANL), to simulate fire behavior for various prescribed fire ignition patterns. The 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 AFB and, (c) use modeling results to enhance knowledge, skills, and abilities of fire practitioners nationally.

The project was designed jointly by Dr. Rodman Linn, a LANL Senior Scientist who developed FIRETEC, and three experienced wildland fire managers from the Air Force Wildland Fire Branch, Eglin Air Force Base, Florida. These three fire managers cumulatively have over 70 years of wildland fire experience on more than 1,000 fire events, primarily in longleaf pine and associated southeastern fuel types. Dr. Linn met with these managers at Eglin to define prescribed fire scenarios to be modeled by FIRETEC that specifically addressed knowledge gaps within the prescribed fire practitioner community. Simultaneously these scenarios were used to test the limits of FIRETEC's ability to model some of the complex ignition patterns common to prescribed fires. This project is a direct result of these original discussions.

1.1 BACKGROUND

Prescribed burning is a critical tool on many DOD installations for minimizing wildfire risk and for managing fire-dependent ecosystems that preserve viability of regional biodiversity, the resilience of ecological processes, and sustainment of military use. Given the vast spatial extent of DOD properties, frequent mission-caused ignitions, and the presence of fire-dependent endangered species such as the Red Cockaded Woodpecker (*Leuconotopicus borealis*), aggressive prescribed fire programs are the only viable option for managing ecosystems on many DOD sites. Currently, to balance the risks and benefits of prescribed fire, DOD and other land management agencies rely on insufficient fire spread models and the institutional knowledge of key individuals accumulating decades of experience at specific sites. However, the complex nature of fire's interaction with ecosystems and the atmosphere results in a steep and often unforgiving learning curve for optimizing site-specific practices (depending on ecosystem, topography, prevailing weather patterns, and vicinity of sensitive sites). Additionally, air quality regulations and the increase in urban encroachment around military installations have further constrained fire managers and reduced the tolerance for failure. Vast areas requiring management, such as DOD and other federal lands, have led to common use of large-scale (1,000+ acre) prescribed fires, often utilizing helicopter ignition, without fire managers having adequate understanding of fire at this scale. This steep learning curve and lack of understanding of rapid ignition dynamics has led to many prescribed fires that are too intense, causing significant damage to natural resources and to smoke incursions that negatively impact both the public and occasionally, military mission activities. This lack of understanding also leads to inefficient use of ignition tools, raising costs unnecessarily in times of shrinking budgets, and to unnecessary risk for firefighters.

In an effort to better understand the phenomenology, propagation, and dynamics of large-scale planned ignitions, this project was designed to demonstrate the modeling capacity of FIRETEC, an R&D 100-winning (Linn et al. 2003) three-dimensional supercomputer code, to simulate a variety of prescribed fire mass ignition scenarios. Current operational fire spread models, such as BehavePlus, FlamMap and FSPPro, are constrained to estimating fire behavior from a single point source and in response to static conditions in a single location. These models do not account for the convective heating, interactions among multiple heat sources, and atmospheric coupling that occur on real-world prescribed fires.

Initial FIRETEC validation efforts were undertaken using data collected from the 2012 Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE) at Eglin AFB, Florida. Data from RxCADRE and Eglin's ecological monitoring program were also used to parameterize fuels and forest structure within the modeling domain for prescribed fire simulations varying in vegetation structure, ignition type, wind speeds, and number of ignition lines.

1.2 OBJECTIVE OF THE DEMONSTRATION

Overall objectives for the project were focused on advancing fire behavior modeling science using a co-production approach that also provides direct benefit to fire practitioners through improved knowledge and training aids. The specific objectives stated for the project are 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 AFB and, (c) use modeling results to enhance knowledge, skills, and abilities of fire practitioners nationally. During project development there was intense focus by the involved wildland fire managers to ensure a project design that, in addition to meeting the modeler's validation requirements also generated data and powerful visual training tools that specifically addressed prescribed fire managers' "burning questions".

1.3 REGULATORY DRIVERS

Regulatory drivers that have produced a need for the improved accuracy of wildland fire spread models primarily include the Endangered Species Act of 1973, the Sikes Act, Department of Defense Instruction (DODI) 4715.03, and Air Force Instruction (AFI) 32-7064.

Endangered Species Act of 1973 - A number of threatened or endangered terrestrial species protected under the Endangered Species Act, particularly in the Southeastern U.S., require fire as a disturbance at some point in their life cycles to maintain their breeding and/or foraging habitat. The large areal extent of many DOD installations, and the corresponding spatial extent of fire-dependent listed species' populations, often necessitate large-scale ignitions to accomplish annual habitat management objectives. On Eglin AFB alone, the federally endangered red-cockaded woodpecker occupies over 250,000 acres of longleaf pine habitat that requires a low intensity surface fire every 1-5 years.

Sikes Act of 1960 – The Sikes Act provides for cooperation by the Departments of Defense and Interior with State agencies in planning and implementing management of natural resources on

military reservations. This act also requires an Integrated Natural Resources Management Plan (INRMP) be developed for any installation possessing natural resources and land base. Many INRMPs, and most in the Southeastern U.S., possess objectives directly related to prescribed fire as a management tool.

DODI 4715.03 – This DOD instruction directs natural resources conservation and ecosystem-based management on all DOD lands. In reference to wildland fire, this instruction specifically requires fuels management in order to reduce wildfire potential and manage ecosystems by implementing prescribed fire where appropriate, and yet DOD fire managers currently lack sufficient technology for accurately predicting complex firing scenarios commonly encountered during prescribed fires.

AFI 32-7064 – This Air Force Instruction, specifically Chapter 13, describes the requirements and standards for wildland fire management on AF installations. It provides details on minimum training, qualifications, and safety requirements for conducting prescribed burns on AF lands.

2.0 TECHNOLOGY/METHODOLOGY DESCRIPTION

2.1 TECHNOLOGY/METHODOLOGY OVERVIEW

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 1, during a FIRETEC wildfire 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.

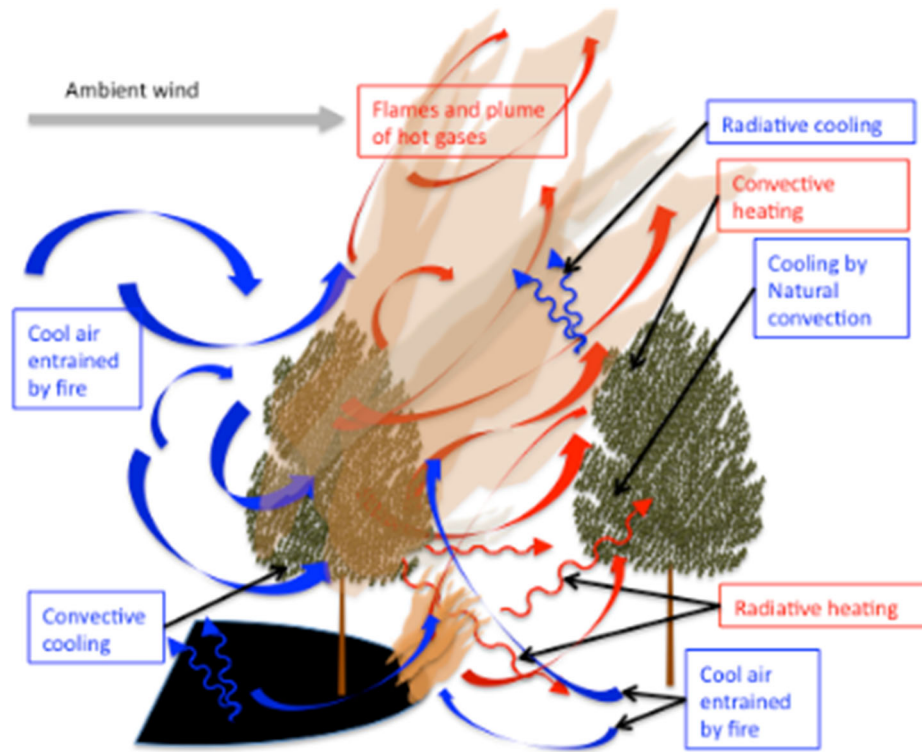


Fig. 1. Multiple interactive physical processes are integrated in FIRETEC simulations.

To accurately represent such interactive fire processes, FIRETEC combines physics models that represent combustion, heat transfer, aerodynamic drag and turbulence with a computational fluid-dynamics (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.

The solution of coupled PDEs that describes the temporal evolution of fire, fuel loads, and the surrounding atmosphere requires prescription of conditions at the start of the simulation as well as the ambient conditions that evolve/persist outside of the simulation domain throughout a simulation, i.e., initial and boundary conditions. These requirements include a spatially-explicit description of the atmosphere and vegetation. Three-dimensional winds, pressure, temperature, gas species concentrations, and turbulence must be designated throughout the entire volume of the simulation-domain initially and at the domain boundaries for the duration of the simulations. As fire releases heat, produces gas emissions, and changes fuel loads (changing aerodynamic drag), the fire “creates its own local weather” inside the domain which continually interacts with

the larger-scale ambient meteorology through the boundary conditions. At any cell within the three-dimensional domain where there is vegetation, fuel characteristics are used to map out horizontal and vertical fuel distributions in a spatially explicit manner (Figure 2). At the onset of a simulation, fuel characteristics are specified at locations of various vegetation species, including: bulk-density, surface-area-per-unit volume, and moisture content. The evolution of these characteristics with time during the simulation is then predicted by the solution of the PDEs as the fire moves through the domain. In scenarios where actual locations and dimensions of trees are not known explicitly, appropriate distributions of plant and tree sizes and shapes for prominent species are used to create realistic and representative virtual ecosystems. This procedure has been honed over the past decade since it was first used to simulate fire in a ponderosa pine ecosystem based on USFS field data (Linn et al. 2005a), and have been used in chaparral, pinyon-juniper (*Pinus edulis* – *Juniperus* spp.), lodgepole pine (*Pinus contorta*), Mediterranean, and now longleaf pine-turkey oak (*Quercus laevis*) ecosystems.



Fig. 2. Representation of three dimensional grid that is required for entire computational domain, including specific information on fuel characteristics.

FIRETEC has been used to investigate facets of wildland fire behavior associated with a wide range of environmental influences, from the local effects of specific tree configurations (Linn and others 2005; Parsons 2007; Pimont and others 2011), to the interaction between separately ignited fires (Depuy and others 2011), to the larger scale effects of evolving weather conditions. FIRETEC has been applied to study basic fire behavior phenomena (Cunningham and Linn 2007; Linn and others 2007, 2010, 2012a; Pimont and others 2006, 2009), and it has begun to be

used to understand implications of simplified fire behavior model formulations (Pimont and others 2012).

The applications of FIRETEC span ecosystems from sparse grass to heavily forested woodlands on both flat terrain and in rugged topography (Linn and others 2007, 2010; Pimont and others 2011). The coupled physics-based formulation of FIRETEC and the range of size scales for which it has been designed (domains of 100s of m² to 10s of km² with resolutions on the order of meters) enables FIRETEC to be used to investigate the interactions between ignition strategies, local meteorology, ecosystem structure, and even fire management practices that result in successful or unsuccessful prescribed fire operations in terms of fire behavior (Cassagne et al. 2011) or emissions transport and fate.

The R&D activities that have led to the development and testing of this tool have been largely funded by Los Alamos National Laboratory Directed Research and Development (LDRD) program and the USDA Forest Service through the National Fire Plan and Joint Fire Science Program (JFSP). The JFSP and LANL Collaborative University of California/Los Alamos Research (CULAR) program funded the development and implementation of the spotting model within FIRETEC, which allows the model to estimate probabilistic trajectories and points of ignition from burning firebrands. In addition, a wide range of US and international collaborators such as Institut National pour la Recherche Agronomique (INRA, France) have contributed in-kind support for the advancement and application of this tool.

2.2 TECHNOLOGY/METHODOLOGY DEVELOPMENT

Under development and refinement since 1995, FIRETEC has been used to simulate, and compare with both historical fires (Bossert and others 2000; Bradley 2002) and field experiments such as the 2005 International Crown Fire Modeling Experiment illustrated in Figure 3. (Linn and Cunningham 2005; Linn and others 2005; Pimont and others 2009; Linn and others 2012b). These simulations have demonstrated this model's ability to capture realistic fire behavior in a variety of situations. Continued efforts to broaden the scope of these comparisons include a current project, in collaboration with Natural Resources Canada, to simulate key aspects of the 2016 Fort McMurray wildfires in Alberta, Canada.

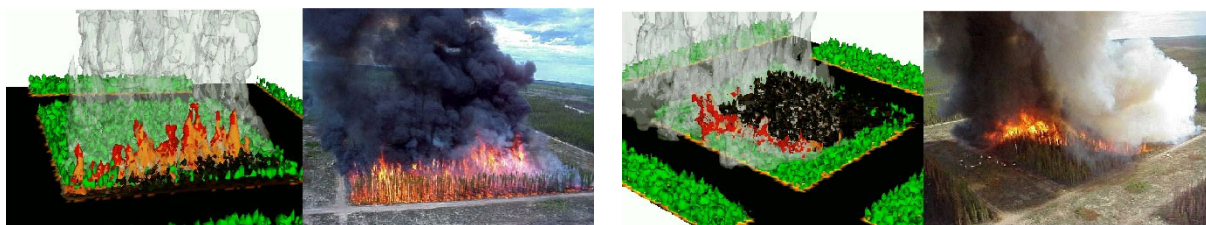


Fig. 3. FIRETEC simulations (left and center-right) paired with photographs (center-left and right) of plot 1 of the International Crown Fire Modeling Experiment, which took place in Canada's Northwest Territories between 1995 and 2001. FIRETEC simulations of several of the ICFME burns produced spread rates and burn patterns that replicated the actual fires well.

Photos courtesy of Natural Resources Canada, Canadian Forest Service.

FIRETEC has also been utilized to simulate key aspects of historical fires, including the 2012 Las Conchas Fire near Los Alamos, NM, and the tragic 1949 Mann Gulch Fire in Montana. These simulations are valuable not only for validating the modeled phenomenology but also for deciphering unexplained or controversial aspects of these fires.

FIRETEC has been used to study the interaction between multiple lines of fire (Figure 4) (Dupuy and others 2011) and the impacts of massive insect attacks on fire behavior in lodgepole pine (Hoffman and others 2015) and pinyon–juniper (Linn and others 2013) ecosystems. In recent years, the State of New Mexico used FIRETEC to examine the effects of fuels management treatments near mountain communities. FIRETEC is not available on desktop computers because it requires large amounts of input data and a supercomputer, but the simulations produced by FIRETEC have far-reaching implications and applications for fire managers. Additionally, lessons learned and resulting model refinement throughout this project are proving useful in the development of a simplified desktop version of a physics-based fire behavior modeling tool.

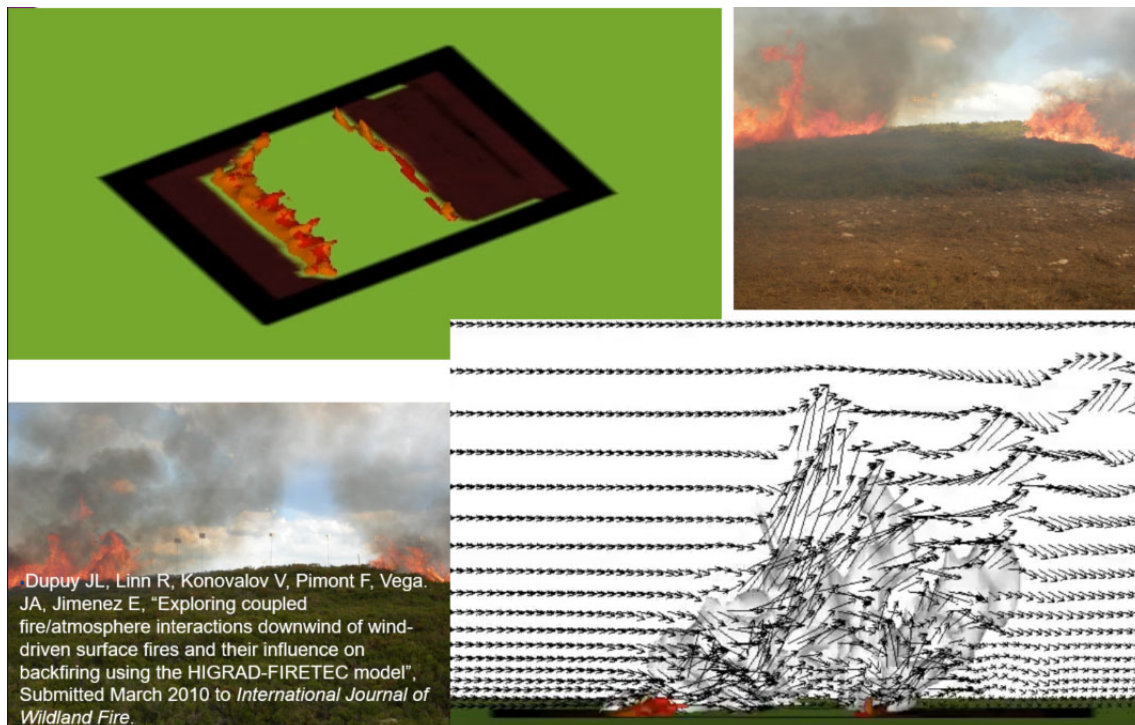


Fig. 4. FIRETEC modeling of the interactions between lines of fire.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY/ METHODOLOGY

Current operational fire-simulation computer models such as BehavePlus and FlamMap are limited by their empirical origins—they rely on extrapolations from a limited set of laboratory

and field-scale experiments that estimate fire behavior in response to set conditions in a single location. These models are not suitable for predicting the coupling between fire and local conditions that result in heterogeneous ecosystem impacts or a wide range of emission transport patterns. These and other widely available spatial fire behavior systems such as FARSITE and FSPRO do not account for convective heating or interactions between multiple heat sources (such as multiple ignitions common in prescribed fire). They are typically limited to a single point of ignition, or treat ignitions as if they are independent with no interactions. They cannot provide explanations of the critical relationships that dictate the sensitive balances occurring in a prescribed fire environment and are unable to identify thresholds of fire behavior that determine success or failure of prescribed fire operations. For example, these models are currently unable to answer questions such as: a) How does distance between lines of fires and multiple ignition points affect fire intensity and plume lofting? b) How does spot ignition moderate fire intensity as compared to line ignition? c) How does unit boundary ignition affect fire behavior and fire effects on the interior of the burned area? d) How do midstory vegetation and other forest structure variables influence wind fields and resulting fire behavior?

As a physics-based fire-behavior model coupled in a two-way fashion with a computational fluid dynamics (CFD) model, FIRETEC overcomes the stated shortcomings of currently available fire spread models by accommodating for multiple heat sources, the driving influence of convective heating, and coupled fire/atmospheric interactions and is providing answers to the above questions through the multiple simulations completed for this demonstration. The primary limitations associated with FIRETEC are the costs and expertise required to program and run the model and the inability of FIRETEC (and perhaps any model) to account for stochastic changes in the fire environment such as unexpected changes in winds and other weather factors. Due to computational power and memory requirements, FIRETEC must currently be run on a supercomputer. For this reason, combined with the fact that it requires staff fluent in the underlying programming code, it is unlikely that a robust physics-based fire spread model such as FIRETEC will be available for operational use by fire managers in the near future, though the results from this project are currently being used to develop a simpler and very promising physics-based fire behavior model called QUIC-Fire that can run on a standard personal computer. Simulations produced by FIRETEC will be instrumental in examining and explaining fire phenomenology produced by complex ignitions common to prescribed fires. Although fire managers will not be able to run FIRETEC for specific planned burns, ignition scenarios explored through FIRETEC model runs have produced an invaluable set of visual models for training and explaining fire behavior to prescribed fire practitioners.

FIRETEC was developed with the assumption that you can model the critical essence of wildland fire behavior and predict the important characteristics of fire behavior without knowing all of the fine-scale details of either the winds (timing of short duration and spatial arrangement of small individual gusts) or fuel (location, shape, and orientation of individual needles or branches.) This assumption and the lack of data regarding these details inherently mean that the precise details of the simulations will often not match the fine-scale details of an experiment, but they should not preclude the representation of the macro-scale fire behavior or atmospheric response.

Fire behavior is the result of coupling a large number of very complex physical processes, and it

is sensitive to both averages and fluctuations in numerous environmental conditions. It is not feasible to measure and represent all of the variations in the vegetation and wind field and thus impossible to precisely model exactly when a wind gust arrives at a fire front in relation to the time when the fire reaches a specific tree. For this reason it is not possible to precisely model the fire effects on particular trees or the timing of specific moments of acceleration of the fire. Instead, the average fire behavior and the nature of the heterogeneity are expected to be similar to those quantities from field data and other field observations at Eglin. Aside from the more comprehensive analysis completed for the RxCADRE S5 burn, the products of this study are intended to provide general guidance for prescribed fire management, and thus focused on phenomenology, fire behavior mechanisms, trends, and sensitivities as opposed to precise details, which would only be valid for a single event.

While the complex set of coupled processes that make up fire behavior are sensitive to environmental conditions that differ from one DOD location to another, extensive experience has shown that (i) the critical questions concerning operational optimization, training, and fire management safety in both aerial point source and strip ignition scenarios are fairly universal, and (ii) the general relationships and trends connecting operational practices to burn success are similar. For this reason, it is expected that the essence of the findings from the work at Eglin will be applicable to other DOD sites, as well as cooperating agencies that widely use prescribed fire, and will establish the foundations for site-specific refinement of guidelines as needed at other sites.

3.0 PERFORMANCE OBJECTIVES

TABLE 1. Performance Objectives

Performance Objective	Metric	Data Requirements	Success Criteria
Quantitative Performance Objectives			
1. Further validate FIRETEC's ability to simulate representative coupled fire/atmosphere behavior	• Ability of FIRETEC to simulate observed fire-influenced wind responses and heat fluxes as measured in RxCADRE fires • Correspondence between FIRETEC and macroscale fire behavior as measured in RxCADRE fires	• Fuels data (type, fine-fuel surface area to volume ratios, bulk density, vertical distributions, moisture distributions) • Pre-fire ambient and fire-induced winds data from anemometers, Doppler LiDAR, SoDAR, and radiosonde soundings • Heat release data (in-situ sensors and radiometers, IR video, remote IR)	• Simulated fire-induced updrafts, ambient winds, and radiative fluxes will be within one standard deviation of values measured from a combination of field measured values from 2008, 2011, and 2012 RxCADRE campaigns. • Modeled fire perimeters accelerate and decelerate directionally and temporally as expected in response to wind shifts measured in RxCADRE.
2. Simulate prescribed fire behavior and phenomena in longleaf pine fuels on Eglin AFB	Ability of model to represent realistic fire behavior in prescribed fire scenarios in longleaf pine fuels on Eglin AFB.	• Fuels datasets for three representative Eglin fuel types (grass, forested, forested with midstory) • Wind field data for these fuel types • Ignition parameters	• 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. • Simulated results capturing known response to changes in ignition configuration including line and spot ignition separation distance under

			different wind and fuels conditions will be within one standard deviation of rates and directions of spread measured in 2008, 2011 and 2012 RxCADRE campaigns.
Qualitative Performance Objectives			
3. Use modeling results to enhance knowledge, skills, and abilities of fire practitioners nationally	• Incorporation of lessons learned into next revision of NFES #1080 Aerial Ignition Guide • Production of firing technique lesson plan and video	Structured feedback, through a facilitated workshop, from fire managers with various levels of expertise on utility and application of demonstration outcomes and lessons learned	• Modeling outcomes incorporated into NFES #1080 • Lesson plan available for download from Wildland Fire Lessons Learned Center and JFSP wildfire consortia websites • Greater than 80% of workshop participants and end users “agree” or “strongly agree” that FIRETEC model demonstration improved their understanding of prescribed fire ignition techniques and resulting fire behavior.

3.1 Performance Objective 1. Further validate FIRETEC’s ability to simulate representative coupled fire/atmosphere behavior

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. In the end, data from the 2012 RxCADRE S5 burn 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 Rx CADRE, was met. 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 Sections 5.2 and 6.1.

3.2 Performance Objective 2. Simulate prescribed fire behavior and phenomena in longleaf pine fuels on Eglin AFB

FIRETEC simulations were used to illustrate the influence of ignition techniques, densities and patterns on fire behavior, wind fields, and emissions lofting and explain the related phenomenological interplay controlling the feedbacks. These simulations were designed to help prescribed fire managers explore the dynamic interplay of fuel structure, wind speed, and ignition patterns on fire behavior and fire spread. Through this exploration, modeled relationships between these variables allowed the project team to investigate management-relevant questions such as: How does the alignment of point source ignitions with respect to local ambient wind affect the intensity of the burn? How does the length of dash-fire ignitions moderate the fire intensity? To what extent might midstory affect prescribed fire operations and ignition techniques? How does igniting the flanking edges of a prescribed fire affect the ventilation of the fire and the intensity of combustion in the interior of the burn unit? Successful simulation was based on the ability of FIRETEC to represent realistic fire behavior including general phenomenology and relative differences in midstory and overstory fuel consumption (as a representation of fire intensity) for different prescribed fire scenarios in longleaf pine fuels on Eglin AFB.

To assess FIRETEC's simulation success for this objective, simulation results were planned to be evaluated by two methods: a) additional comparison with RxCADRE field data, and b) evaluation of simulation results by fire managers and practitioners. Rigorous comparison with RxCADRE field data, particularly in the forested experimental burns was problematic due to insufficiency of wind and fuels data for comparison with model results. More detailed information on challenges related to use of RxCADRE data for modeling comparisons is referenced in Sections 5.2 and 6.1.

For peer evaluation, the perceived accuracy of model simulation outputs and results were qualitatively evaluated by fire management and fire science experts with experience in longleaf pine fuel types. FIRETEC simulations were summarized and presented at workshops and meetings to a wide range of wildland fire experts, ranging from practitioners (firefighters, burn bosses, firing bosses, fire behavior analysts) to fire scientists (researchers, modelers, fire ecologists). Workshop participants were asked to evaluate the perceived model accuracy by completing Likert surveys. The criteria for performance objective success derived from the Likert surveys is that greater than 70% of fire managers respond that they "agree" or "strongly agree" that FIRETEC captured the critical aspects of fire behavior and spread in model simulations. This criteria was easily met. The Likert survey form, including consolidated responses is included as Appendix D.

3.3 Performance Objective 3. Use modeling results to enhance knowledge, skills, and abilities of fire practitioners nationally

A primary goal of this demonstration was to provide powerful visual training tools to better educate current and future prescribed fire managers regarding the influence of ignition rates and

patterns on fire behavior under varying combinations of wind speed and canopy structure. In addition to general knowledge improvement, the underlying causal mechanisms of fire phenomenology can be conveyed visually with a physics-based model like FIRETEC. Criteria used to measure success were, a) whether modeling outcomes are incorporated into NFES #1080, Aerial Ignition Guide, b) whether the lesson plan produced from this demonstration is available for download from the Wildland Fire Lessons Learned Center and JFSP wildland fire consortia websites, and c) summaries of Likert surveys administered to fire managers and practitioners assessing the utility and applicability of these educational tools. At the time of the writing of this report, work was ongoing regarding incorporating the project results into the Aerial Ignition Guide. The training video, a recording of the first facilitated workshop, is currently available online at: <https://youtu.be/3E9KxcoVdP8> and is available from the Southern Fire Exchange (one of the Joint Fire Science Consortia) website. Likert survey results from the workshops easily met the thresholds for this objective and can be found in Appendix D. More specific information on outreach activities is included in Section 6.3. Perhaps the most important outreach success is that the Interagency Prescribed Fire Training Center is now incorporating this project's FIRETEC simulations and data into its national training curricula where it will be formally disseminated to hundreds of prescribed fire practitioners across the country in the coming years.

4.0 SITE DESCRIPTION

Eglin AFB was chosen as the test site for this project for the following reasons: 1) Eglin manages one of the nation's leading prescribed fire programs, completing 100+ prescribed fires on approximately 36,500ha (90,000 acres) annually, and is well-networked within DOD and the prescribed fire community in the Southeast, 2) most of Eglin's fires occur in longleaf pine forests, which are of significant conservation interest/concern for DOD as well as other land management organizations in the Southeast, 3) over the years, Eglin wildland fire managers have facilitated a strong cooperative working relationship with the fire research community, 4) Eglin's ecological monitoring program maintains robust vegetation, fuels and forest structure data, 5) the RxCADRE experiments, which included the most heavily-instrumented prescribed fires to date, were conducted at Eglin AFB in 2008, 2011 and 2012, and provided additional data critical for model inputs and evaluation, and, 6) in 2012 Eglin was established as the Air Force Wildland Fire Branch, providing leadership and training for wildland fire activities (both prescribed fire and wildfire management) across the Air Force. For these reasons, Eglin was uniquely positioned to support the project, disseminate the project's findings to fire practitioners, and incorporate the findings into future training and fire management practices.

Since the late 1990s, Eglin AFB wildland fire management has been guided by science-based adaptive management. By working collaboratively with the fire research community, the Eglin wildland fire program is continually evolving in step with the best available science. Perhaps the largest and most involved fire research effort at Eglin, in which Eglin played a central role as host site, was RxCADRE. RxCADRE consisted of collaborative efforts involving more than 90 scientists in a series of highly instrumented prescribed fires. Funded primarily by the Joint Fire Science Program (JFSP) to provide a "Dataset for Fuels, Fire Behavior, Smoke and Fire Effects Model Development and Evaluation", it provided a unique opportunity for the evaluation of FIRETEC's performance in prescribed fire scenarios.

In addition to the selection criteria described above, Eglin AFB has always promoted partnerships and collaboration with local, regional, and national partners. Locally, Eglin is a partner in the Gulf Coastal Plains Ecosystem Partnership (GCPEP), a collection of federal, state, and private landholders with shared boundaries and conservation challenges. Eglin interacts directly with these local stakeholders through GCPEP's steering committee and fire subcommittee. Regionally, Eglin is actively engaged, serving on the steering committee for the North Florida Prescribed Fire Council, and on the advisory board of the Southern Fire Exchange, a JFSP-funded consortium aimed at facilitating the link between fire management and research. Nationally, Eglin has served as host to the interagency Prescribed Fire Training Center since the 1990s and has hosted fire managers from across DOD and other agencies that either visit to work on their fire qualifications or learn more about the Eglin program. Related to training and capacity for outreach, the project Principle Investigator and one of the Co-PIs serve as instructors at the National Advanced Fire & Resource Institute (NAFRI) as cadre for the RX-510, Advanced Fire Effects course.

4.1 SITE LOCATION AND HISTORY

With 724 square miles of land area and airspace overlying 124,642 square miles of water ranges in the Gulf of Mexico, the Eglin Military Complex is one of the largest Air Force bases in the world and is the largest forested military reservation in the United States. The main reservation is located within Santa Rosa, Okaloosa, and Walton counties in northwest Florida (Figure X). Eglin also manages a small parcel (962 acres) in Gulf County, Florida, Cape San Blas. Within the Eglin Range Complex, approximately 14,000 acres are “improved” (urban), 46,000 acres are “semi-improved” (primarily cleared test areas), and 405,000 acres are “unimproved” (primarily forested).



Fig. 5. Map of Eglin AFB reservation

The size of the Eglin Reservation and its diversity of terrain and vegetative cover make it an ideal setting in which to conduct a variety of test and training operations. Environments include shoreline, rolling hills, dense forest, cleared flat expanses, and multiple water environments. Eglin has more than 50 distinct test areas, 436 tactical training areas (TTAs), and sites embedded in a single contiguous land area adjacent to the Gulf of Mexico. This unique setting and overwater airspace combine to provide a sea-to-land transition area—a vital resource for modern weapons system research, development, testing, training, and evaluation. Additionally, multiple special operations groups and other ground training units utilize Eglin’s vast interstitial areas and adjacent water assets.

Prior to its designation as Eglin AFB, most of the land base was under the management of the U.S. Forest Service as the Choctawhatchee National Forest. Eglin AFB was established on June

14, 1935, as Valparaiso Bombing and Gunnery Base, but was soon renamed Eglin Field. In 1940, the U.S. Forest Service (USFS) ceded the 800 square mile Choctawhatchee National Forest to the War Department, and inholdings were consolidated through eminent domain. Soon thereafter Eglin became a gunnery training site for Army Air Corps fighter pilots, as well as a major testing center for aircraft, equipment, and tactics, ranging from night reconnaissance techniques to destruction of underwater obstacles. After the end of World War II, Eglin activated the First Experimental Guided Missile Group, which developed the techniques for missile launching and handling, established training programs, and led in the development of drones. Then in 1949, the Air Force established the Air Force Armament Center at Eglin, which for the first time brought development and testing together.

Eglin has an extensive history of natural resource use prior to its establishment as a military reservation, the majority of which relates to naval stores and timber harvesting of longleaf pine in the 1800s and early 1900s. The majority of Eglin's forests are secondary, having been cut-over at least once, but Eglin still contains more old growth longleaf pine than any other single landholding. The USFS's Choctawhatchee National Forest Management plan written in 1939 describes the forest floor to be sparsely vegetated with little leaf litter. This was attributed to "...the frequency of past fires over the area." The Eglin landscape began to change dramatically when the USFS and later Eglin AFB instituted fire suppression policies. In 1989, prescribed fire was reintroduced on a significant scale at Eglin by the Natural Resources Section, due to Endangered Species Act concerns and military range sustainment needs.

The Eglin Reservation is unique because of the depth and breadth of testing and training that occurs there. All phases of munitions life cycle support occur on the Eglin Reservation from research through sustainment testing. Additionally, various operational units train on the Reservation. This interplay of units, all focused on ensuring our nation's security, generates a synergism that cannot be quantified. Mission activities at the Eglin Reservation today fall into four broad categories:

- Weapons system research, development, test, and evaluation
- Training
- Space operations
- Base and Reservation support

Eglin AFB is the host to the Navy Explosive Ordnance Disposal School (NAVSCOLEOD), Army Ranger Training School (Jungle/Swamp Phase), and the 20th Space Command (20 SPC). Eglin provides ranges and airspace for Air Force Special Operations Command (AFSOC), the U.S. Navy's 5th and 6th (Flight) Training Air Wings (TRAWING 5 and TRAWING 6), and the Army 7th Special Forces Group 7SFG. It is the home of the Joint Strike Fighter (JSF) Initial Joint Training Site and includes a U.S. Coast Guard Station on Okaloosa Island. The Eglin Test and Training Complex (ETTC) provides an armament and multispectral test and training environment, which is a DOD-unique land-sea interface with contrasting background and clutter environments that are essential for munitions seeker testing.

The land is used for the testing, development, and evaluation of weapons systems and methods of warfare. The land is also used for live-fire ranges and military tactical maneuvers. There are

five operational airfields within the Eglin Reservation. Frequent munitions testing and live fire exercises provide more than adequate ignition sources within the context of an easily ignitable and highly flammable mix of fuel types typical of longleaf pine forests. As a result, Eglin AFB wildland fire managers respond to an average of 50-75 wildfires per year, 90% of which are mission-caused.

The 96th Test Wing (96 TW) manages the Center's test and evaluation mission and oversees a variety of specialized test facilities at Eglin. The 96 TW is the Range Operating Authority of the Eglin Range complex (airspace, land, water, and frequency spectrum), one of the key Air Force components to the DOD Major Range and Test Facility Base (MRTFB), a national asset composed of unique range and facility assets across the country tasked to support execution of the DOD research, development, test, evaluation and acquisition mission. The 96 TW is the test and evaluation center for Air Force air-delivered weapons, navigation and guidance systems, Command and Control systems, and AFSOC systems. The wing provides expert evaluation and validation of the performance of systems throughout the design, development, acquisition, and sustainment process to ensure the warfighter has technologically superior, reliable, maintainable, sustainable and safe systems. The 96 TW performs developmental test and evaluation across the complete system life cycle for a wide variety of customers, including Air Force Systems Program Offices, the Air Force Research Laboratory, logistics and product centers, major commands, other DOD services and U.S. government agencies (Department of Transportation, National Aeronautics and Space Administration [NASA], etc.), foreign military sales, and private industry.

4.2 SITE CHARACTERISTICS

The most extensive natural community type on Eglin AFB is longleaf pine sandhills, which cover approximately 70 percent of the base. Longleaf pine sandhills are characterized by an open, savanna-like structure with a moderate to tall canopy of longleaf pine, a sparse midstory of oaks and other hardwoods, and a diverse groundcover comprised mainly of grasses, forbs and low stature shrubs. The structure and composition is maintained by frequent fires (every one to five years), which controls hardwood, sand pine (*Pinus clausa* var. *immuginata*) and titi (*Cliftonia monophylla* and *Cyrilla racemifera*) encroachment. Longleaf pine sandhills consist of a high diversity of species adapted to fire and the heterogeneous conditions that fires create. Variation within the sandhills is recognized by the two associations differing in the dominance of grass species (wiregrass versus bluestem).

Sandhills are often associated with and grade into scrub, upland pine forest, xeric hammock, or slope forests. Sandhills are also known as longleaf pine turkey oak, longleaf pine-xerophytic oak, longleaf pine-deciduous oak, or high pine. The functional significance of the Sandhill Matrix is to provide maintenance of regional biodiversity. Additionally, the sandhills, due to their wide coverage on Eglin, are the matrix across which fire carries into the other imbedded fire-dependent systems. Eglin AFB is the largest and least fragmented, single longleaf pine ownership in the world, and has the largest amount of remaining old growth longleaf pine. Seepage slopes are a common embedded wetland feature found within Eglin's sandhill matrix.

Sandhills habitats, important for a number of federally listed species, degrade without frequent fire. Infrequent fire results in a dense midstory of evergreen oak, other hardwoods, and sand pine which in turn inhibit groundcover and groundcover-produced fuels needed to carry fire. In sandhills, the forest structure is mixed, as described above, with variation in midstory hardwood density and overstory pine density and distribution, while cleared test areas at Eglin include a combination of bunchgrasses and low deciduous shrubs. Forest structural condition is known to play an important role in wind dynamics, both horizontally and vertically, and in turn influence rates and directions of fire spread. Forest structure varies seasonally due to the deciduous nature of many of the oaks on Eglin that make up the sandhills midstory. The shape and position of burn units with respect to roads, streams and open test areas can also significantly influence fire spread and behavior in concert with ambient wind and weather conditions. Pine litter, grasses, and low hardwood shrubs, primarily oaks, are the primary fire carriers in Eglin sandhills, and these fuels vary in their contribution to fire behavior and heat flux based on arrangement and diurnal moisture contents.

5.0 PROJECT DESIGN

This project was specifically designed and co-managed by fire managers and the developer of FIRETEC in order to provide immediate tangible benefit to both the prescribed fire community and fire modelers.

5.1 CONCEPTUAL PROJECT DESIGN

Overall project design is illustrated by the schematic in Figure 6. Each of the three black boxes in the center represents a series of FIRETEC simulations, which are described in more detail in the following sections.

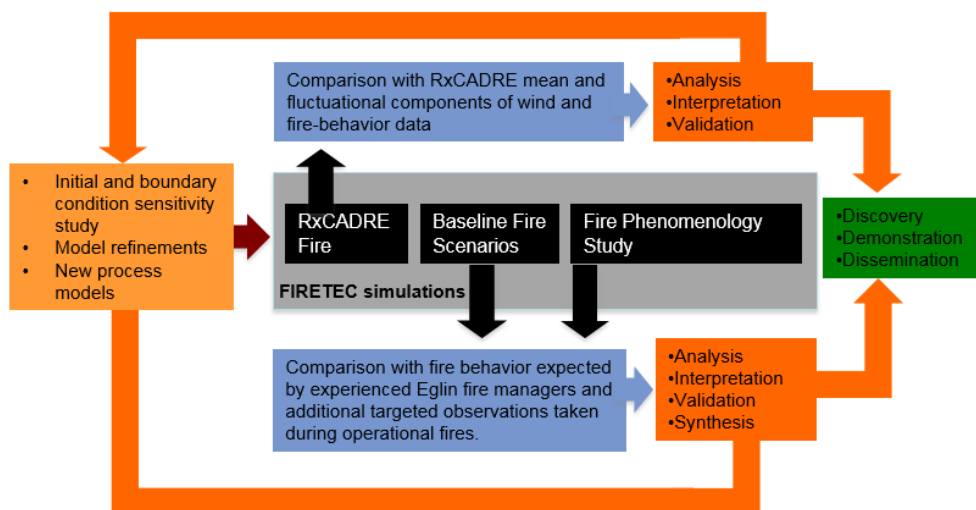


Fig. 6. General project schematic. The gray box contains three sets of FIRETEC simulations (the black boxes). Each relates to a different component of the project. “RxCADRE Fire” simulations are run with and compared to data from a 2012 RxCADRE fire (top blue box). Analysis and interpretation from the RxCADRE simulation (upper red box) provide information for the outreach element of the project (green box) as well as the sensitivity study and model refinements (orange box on left). This in turn provides information for improving the FIRETEC simulations for analysis, interpretation, validation, and synthesis (lower red box). “Baseline Fire Scenarios” and “Fire Phenomenology Study” simulations were designed to test FIRETEC’s ability to capture realistic phenomenology associated with variations in environmental conditions and ignition strategies. These simulation results are compared to fire behavior expectations from experienced fire managers (lower blue box). Analysis and interpretation of these simulations, as with the RxCADRE simulations, provide information for discovery and outreach.

5.1.1 Model Comparison with RxCADRE Fire

This component of the ESTCP project was comprised of an analysis and comparison of FIRETEC simulations using fuels and weather data from a highly instrumented RxCADRE burn conducted in 2012 at Eglin AFB. The “S5” burn block was chosen for this comparison. More specific information on the S5 burn block and the RxCADRE phase of the project is available in Section 5.2.

5.1.2 Baseline Fire Scenarios

Within the gray box in Figure 6, “Baseline Fire Scenarios” refers to a series of FIRETEC simulations that were used to explore and illustrate fundamental sensitivities associated with aerial point source ignition and strip-ignition techniques under moderate and low-wind scenarios. These are described in more detail in Figure 7. In this figure, each of the 18 small black squares within the green box represents a simulation with the number of ignition lines shown in the black box and the wind speeds, ignition type and vegetation structure shown in the blue boxes above the black boxes in the tree. The simulations were designed to explore and demonstrate FIRETEC’s sensitivity to different vegetative structure, wind speeds and ignition strategies. In order to explore and demonstrate the impacts of vegetation structure on fire behavior, three different vegetation conditions were simulated: “grass”, “canopy”, and “canopy with midstory”. Both canopy and canopy-with-midstory conditions include appropriate grass and litter loads as well. Canopy with midstory is the most important vegetation structure or fuel type to model for prescribed fire purposes because this represents the forest conditions under which most prescribed fires occur in the Southeast. The presence of midstory vegetation generates a more complex wind field due to vegetative drag and the resulting wind turbulence. However, it is valuable to simulate fire in the other two conditions in order to determine and demonstrate model sensitivity to the impacts of the canopy and midstory fuel structure on wind fields and resulting fire behavior. For each of these vegetation conditions, fire was simulated with a single strip ignition under both moderate (5.36 m/s or 12 mph) and low (2.23 m/s or 5 mph) wind speeds at a height of 24 m. For canopy with midstory, additional simulations were completed using multiple ignition lines for each wind speed (2, 4 and 6 line ATV/ground ignitions and 5, 10 and 15 line aerial point source ignitions). These ignition line scenarios were chosen, based on common practices at Eglin AFB, to explore the interactions between multiple ignition lines in representative prescribed fire scenarios.

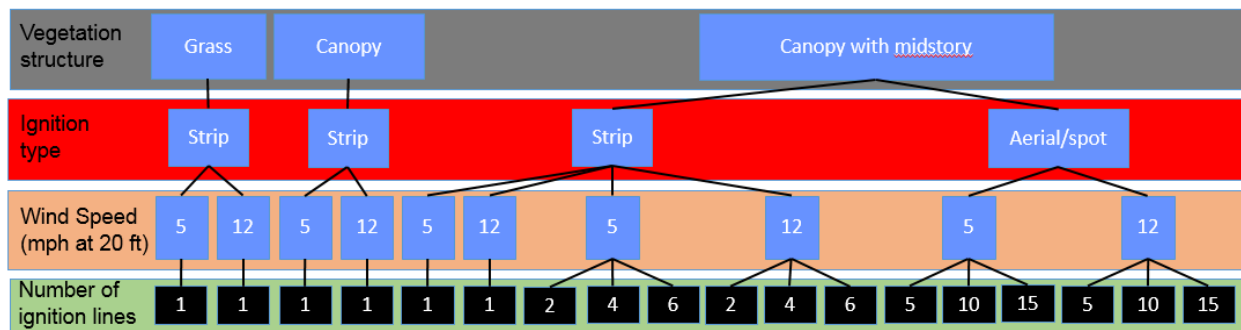


Fig. 7. Schematic of 18 baseline FIRETEC simulations. Each black box represents a model run.

5.1.3 Fire Phenomenology Study

Following the baseline simulations listed in Figure 7, more focused model runs were performed to identify key trends in phenomenology that should be useful to fire managers. Initial planned simulations associated with these studies are illustrated in Figure 8, in which the gray boxes indicate simulations leveraged from the baseline scenarios in Figure 7, and black boxes represent additional simulations.

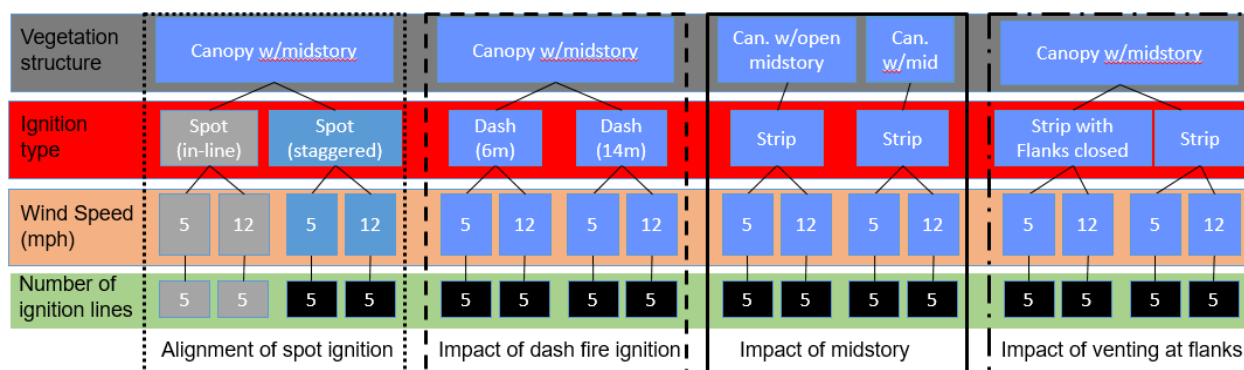


Fig. 8. Schematic of prescribed fire phenomenology study simulations. Gray boxes indicate FIRETEC model runs leveraged from baseline simulations in Figure 7.

With these simulations the project team investigated such management-relevant questions as: How does the alignment of aerial point source ignitions with respect to local ambient wind affect the intensity of the burn? How does the length of dash-fire ignitions moderate fire intensity? To what extent might the midstory affect prescribed fire operations and ignition techniques? How does connecting the flanking edges of strip fires affect the ventilation of the fires and the intensity of the combustion in the interior of the burn unit? Most of the scenarios (wind, fuel types, and ignition patterns) intentionally mimic those of typical prescribed fire conditions in order to demonstrate the ability of FIRETEC to capture trends in fire behavior/phenomenology in these scenarios. Others were specifically designed to explore knowledge gaps that affect prescribed fire planning and implementation. The project design allowed FIRETEC’s performance to be assessed for its ability to appropriately predict the expected fire phenomenology for varying firing techniques under the same environmental conditions. For example, as more fire is applied per unit area, modeled fire behavior should become more intense, e.g. point source (“aerial”) firing pattern should burn less intensely than dash ignitions, which should burn less intensely than strip head fire for the same number of ignition lines. Each of the simulation sets in Figure 8 are discussed in more detail below:

5.1.3.1 Alignment of spot ignitions- Specialized equipment used by land management agencies allows aerial point source ignition from a helicopter by dropping plastic spheres that provide delayed ignition from an exothermic chemical reaction. Ignition rates using this method can exceed 400 hectares (1,000 acres) per hour. While it is understood that accurately aligning, or perfectly staggering, point source ignitions from a helicopter igniting perpendicular to prevailing winds is impossible, this scenario set was designed to explore impacts of point source alignment with respect to each other. FIRETEC simulations using “aligned” and “staggered” firing patterns were performed to see if FIRETEC simulations suggest that alignment can significantly influence fire intensity. Though much slower than aerial point source ignition, point source ignition is also a common technique used when setting a prescribed fire by hand or when using an ATV mounted torch. Either of these ignition methods makes the ability to align or stagger ignition points more feasible. Thus, differences in overall modeled fire intensity between in-line and staggered aerial point source ignitions could provide insights useful to fire managers for non-aerial, point source ignition strategies.

5.1.3.2 Impact of dash fire ignition- The prescribed fire ignition strategy of lighting varying lengths of dashes, perpendicular to the prevailing wind direction, is recognized by fire managers as a way to moderate overall fire intensity as compared to setting solid lines of fire (strip head fire). The conventional wisdom is that dash firing produces less head (wind driven) fire and more flanking fire, which spreads more or less parallel to the wind direction and is typically lower intensity than head fire. Also, leaving space between dashes allows more cool air entrainment and opportunities for convective cooling to occur. The decision to model fire behavior produced by two prescribed fire scenarios that use different lengths of dashes was based on the expectation that these scenarios would serve as a natural bridge for comparison between point-source (least amount of fire applied per unit area) and strip head fire (greatest amount of fire applied per unit area). After some experimentation, dash lengths of 6m and 14m were used. Unlit strips between dashes were standardized at 40m.

5.1.3.3 Impact of open midstory- The impact of an open midstory on fire behavior was included in the project for a number of reasons. If longleaf forests are burned frequently, the midstory will be reduced in stature and create a corresponding reduction in fuel loadings. An open midstory decreases wind drag, increasing in-stand winds as compared to a stand with a heavier midstory component. An open midstory represents the desired future condition for most managers of longleaf pine forests, so was important to consider for this project.

5.1.3.4 Impact of venting at flanks- Most wildland firefighters are taught early in their careers that one of the “Watch Out Situations” is having unburned fuels (vegetation) between them and the fire. For many, seeing this situation automatically leads them to set fire from the fire line to “create black”. While this is often a viable choice for fighting wildfires, in the prescribed fire arena it often causes unnecessarily intense burning that damages resources. Since one of the objectives of the project is to enhance training for prescribed burners, the project team included a FIRETEC simulation that visually illustrates the fire behavior response that occurs when a prescribed fire’s flank is lit to serve as a visual training tool.

5.1.4 FIRETEC Baseline and Phenomenology Study Parameters

5.1.4.1 Dimensions

The size of the computational domains was chosen as a balance between simulation realism and computational requirements. In FIRETEC simulations, the fire must be able to freely affect the winds around it. If the domain boundaries are too close to the fire, they inhibit fire/atmosphere feedbacks such as indrafts and plume dynamics. At the same time, the larger the computational domain, the greater the computational expense. As illustrated in Figure 9, computational domain dimensions for this project were 500m x 1200m x 615m for all “ATV” ignitions and 900m x 1200m x 615m for the largest aerial point source ignition simulations. Distance between parallel firebreaks for all simulations was 802m. This allowed an unburned buffer of 198m on each flank. For the ATV ignitions, the downwind firebreak was 353m from the upwind (left) side and for the aerial point source ignitions it was 783m from the upwind side. This allowed adequate unburned buffers for both the upwind and downwind side of the simulations.

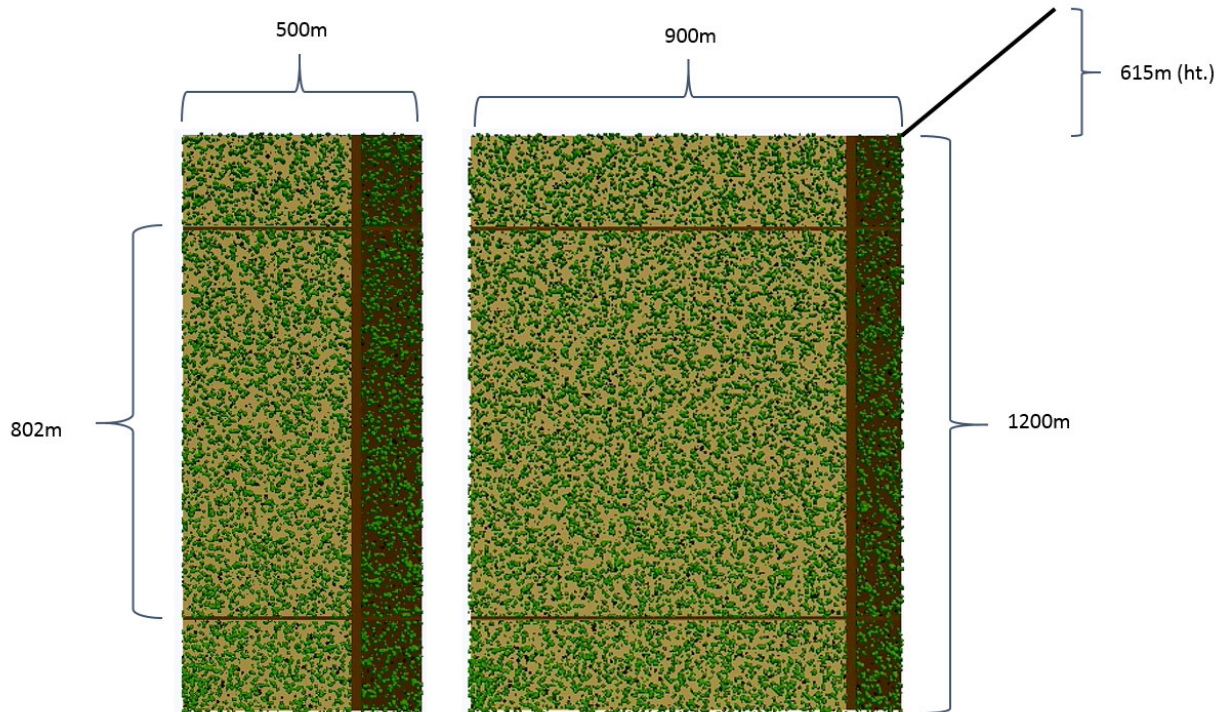


Fig. 9. Computational domain dimensions for ATV/ground ignitions (left) and the largest aerial ignitions (right).

5.1.4.2 Fuels

For the simulations described in Figures 7 and 8, FIRETEC required a detailed description of the fire's environmental conditions as well as the ignition parameters. To define the fuelbed, the bulk density, surface-to-volume ratio, vertical distribution, and moisture content of the fuel was specified in every cell in the 3-dimensional grid within the computational domain. To generate these inputs, Eglin fuelbed datasets for grass, forested, and forested with midstory community types were used, including Eglin long-term sandhills monitoring plot data. Key tree and shrub species parameters include fine fuel bulk density, canopy size (diameter and height), and crown dimensions. Important surface fuel variables include fuelbed depth, composition, bulk density, and live/dead fuel moisture. Surface fuel loading was homogenized across the fuel bed for all scenarios at 0.79 kg/m² (3.5 T/ac) with a depth of 0.5m (1.64') and grass/litter fine dead fuel moisture (FDFM) of 8%. For all "Canopy" scenarios, overstory longleaf pine and turkey oak fine fuels were added. Fuel moisture for longleaf canopy foliage for the simulations was set at 133%. For a majority of the simulations, the fires were assumed to be during the dormant period where the leaves on turkey oak are dead with a FDFM of 15%. For "Canopy with midstory" scenarios, small (<~4 m or 13' tall) turkey oak with FDFM of 15% are added at densities based on monitoring plot data for Eglin longleaf pine sandhills. Appendix B includes additional information on fuels.

5.1.4.3 Weather

For this project, two wind scenarios were developed, representing typical low (2.235 m/s or 5 mph) and moderate (5.36 m/s or 12 mph) prescribed fire wind speeds at a height of 24m (78.7',

or 20' above the average canopy height). HIGRAD, the model that provides the fluid dynamics components of FIRETEC, was used to generate wind fields with dynamic turbulence (including heterogeneous and dynamic wind gusts) that are consistent with the spatially varying canopy structures. HIGRAD simulations using periodic boundary conditions to capture the effects of a very long upwind fetch, were used to produce time series of fluctuating winds for every cell around the computational boundary for each type of fuelbed. These winds were then used to provide boundary conditions for simulations using all ignition scenarios in a given type of fuelbed and wind case. Initial air temperature at ground level for all simulations was 300K (26.8C / 80.3F). The effects of humidity on fire behavior were captured through specification of fuel moistures.

5.1.4.4 Ignition Patterns

Ignition parameter inputs were based on common ignition patterns used on Eglin to ignite prescribed fires. For all initial multiple line ignitions, lines of fire are 46m (150.9') apart, with the first ignition line 22m (72.2') from the baseline (downwind) firebreak. For ATV ignition simulations, the firing rate for each igniter is 3.35 m/s (7.5 mph) so the maximum area ignited, using 5 igniters is 16.5 ha (40.9 acres)

Aerial point source ignition patterns were achieved by simulating a helicopter flight pattern with markers being placed in the "burn block" to represent dropped ignition spheres. The 2m resolution of the FIRETEC grid was not sufficient to explicitly simulate the growth of fires from the ignition sphere size to fires on the order of 4m in diameter. Therefore, a uniform time delay was imposed for each of the ignitions to get through this early fire growth stage, and the explicit simulation of the ignitions begins when the fire has grown to ~ 4m x 4m (2 x 2 computational cells). Since the delay time was the same for all of the aerial point source ignitions and the timing of the start of the ignition pattern was arbitrary with respect to the wind, there is no noticeable net effect of the delay in growing from the ignition sphere to ~ 4m.

The maximum ignition area (15 ignition lines) for aerial point source ignition simulations was 51.7 ha (127.8 ac.). Helicopter forward speed was 22.35 m/s (50 mph), taking 10 seconds for turnaround at the end of each ignition line. Within each ignition line, there was 30m (98.4') between individual ignition points, yielding 7.8 ignitions/ha (3/ac.).

5.1.4.5 "Containing" the Fires

Firebreaks were represented as very short grass with 300% fuel moisture in order to induce a small amount of aerodynamic drag in FIRETEC simulation fuel beds and to prevent fire spread outside of the "burn block". Firebreaks 20m wide on the downwind side and 8m wide for the two flanks were established. Although in typical prescribed fire scenarios a backing fire, or "blackline" is first set immediately adjacent to the downwind control line and allowed to back into the unit, thereby essentially widening your control line under low intensity (easy to control) fire behavior prior to igniting the interior of the burn unit, this specific technique was not simulated due to computational cost. Instead, areas downwind of the simulated fires had all fuels below 3m removed from the fuel bed, as if recently burned, allowing head fire to be set upwind of the downwind firebreak. These features are clearly visible in Figure 9. This system of firebreaks and fuel removal downwind was used as a surrogate for fire containment crews on scene. It is interesting to note that prior to widening the fire breaks and removing the fuels from

the downwind side, there were instances of the modeled fire escaping the planned burn area from both downwind and flank sides as may be expected with unsecure lines.

5.1.5 Additional Completed Simulations

As the project was being developed, it was anticipated that the original series of simulations would prompt questions that would warrant further investigations with FIRETEC. Figure 10 illustrates some of the additional simulations that were completed. Brief descriptions of each are included below.

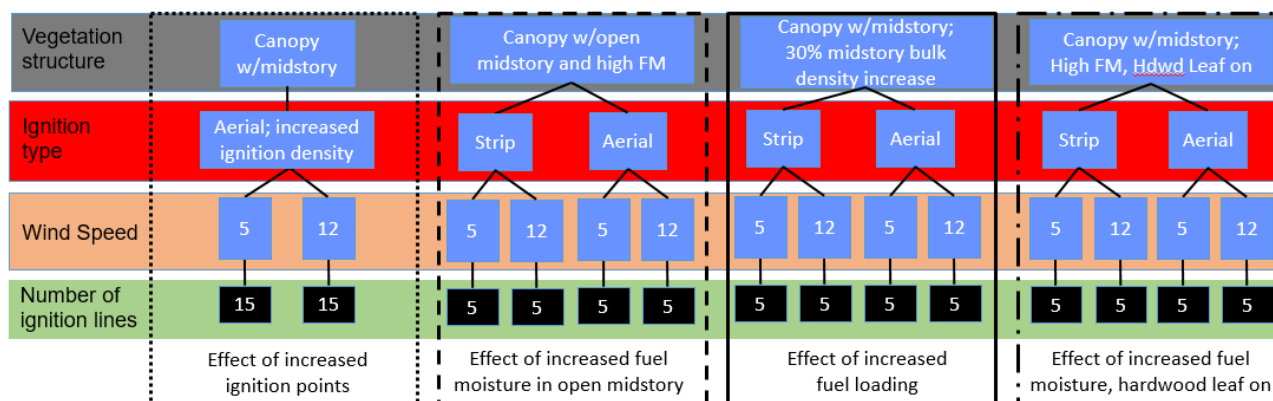


Fig. 10. Additional completed simulations.

5.1.5.1 Increased ignition density for spot ignition: Fifteen line aerial point source ignitions with a doubling of ignition points were completed to explore the modeled effects on fire intensity in relation to ignition point density. So, instead of 150ft and 100ft spacing it was 150/1.414ft and 100/1.414 ft, or 106.1 between ignition lines and ~70.7ft between ignition points in the lines.

5.1.5.2 “High fuel moisture” in “Open midstory”: This represents the environmental conditions that should produce the lowest overall fire intensities. “Open midstory” input conditions for FIRETEC are based on Eglin ecological monitoring data for a plot with high fire frequency and corresponding minimization of midstory fuels. As discussed above, the “high fuel moisture” represents vegetation in the wet, growing season.

5.1.5.3 Increased midstory bulk density: In order to explore FIRETEC’s sensitivity to changes in fuel parameters, several simulations were performed where bulk density of the midstory was increased by 30%. All other parameters were kept the same.

5.1.5.4 “High fuel moisture” simulations with hardwood leaves on: These simulations were performed for several scenarios in order to model fire behavior under variable fuel conditions. Fuel moisture for the turkey oak overstory and midstory was increased from 15% to 200% to represent their leaf moisture content during the wet, growing season. In addition, small (<2m, or 6.5’) persimmon (*Diospyros virginiana*) were added to the midstory in densities based on Eglin AFB monitoring plot data (223 stems per acre) with a live fuel moisture of 170%. All other environmental inputs to FIRETEC remained unchanged.

5.2 BASELINE CHARACTERIZATION AND PREPARATION

This section focuses specifically on the RxCADRE phase of the project where data from the S5 experimental fire were used as inputs for FIRETEC in order to compare FIRETEC's performance to the S5 burn. S5 was chosen out of the several possible 2012 RxCADRE plots due to the fact that it had the most consistent fire behavior and spread. That being said, it is important to note that, even with the most consistent fire spread of all the highly instrumented small plots, burning conditions on the S5 study area were considered "marginal" due to relatively light winds and somewhat sparse fuels. In particular, the fuels had poor horizontal continuity due to patches of bare sand as well as interspersed areas with species such as woody goldenrod, (*Chrysoma pauciflosculosa*) which do not burn well even under good burning conditions. Fuels are discussed in more detail in 5.2.2 below.

To simulate the RxCADRE S5 burn with a wildland fire behavior model, it is necessary to account for fuel configurations and conditions before the fire is started as well as atmospheric conditions at the location of the fire when it is ignited and upwind conditions throughout the lifetime of the fire. This means something different for different kinds of models. The more detailed the model formulation, the more opportunity to represent the actual fire conditions and avoid simplifying assumptions (which are unfortunately often unstated.) However, this flexibility comes with a requirement of more detailed and explicit specification of fuels and winds

For process-based models such as FIRETEC, fuel properties and winds must be specified explicitly throughout the three-dimensional grid at the beginning of the simulation. After the simulation is started, evolving upwind wind conditions can be specified in cells near the upwind boundaries of the computational domain as functions of time. This provides significant freedom for users to account for variability in fuel and wind fields. However, exercising this freedom to capture the conditions of actual fires such as the RxCADRE S5 burn requires data to support the specification of fuels and winds at this level of detail. Without such data, assumptions concerning the mean and variability of fuels and winds must be made.

5.2.1 RxCADRE S5 Winds Characterization

As a part of the RxCADRE experiment, 27 tower-based anemometers were distributed around the S5 plot and in the expected upwind direction of the plot as seen in Fig. 11 (Clements *et al.* 2016). The 24 anemometers surrounding the S5 plot were spaced approximately 30 m from each other and 40 m from the Northwest (planned upwind) S5 plot boundary, 30 m from the Southeast (planned downwind) S5 plot boundary, and 20 m from the other S5 plot boundaries. In reality the winds were closer to being out of the North instead of the Northwest. Three additional anemometers were arranged in a line stretching to the Northwest of the plot since this was the direction from which the wind was expected to come towards the plot during the burn.

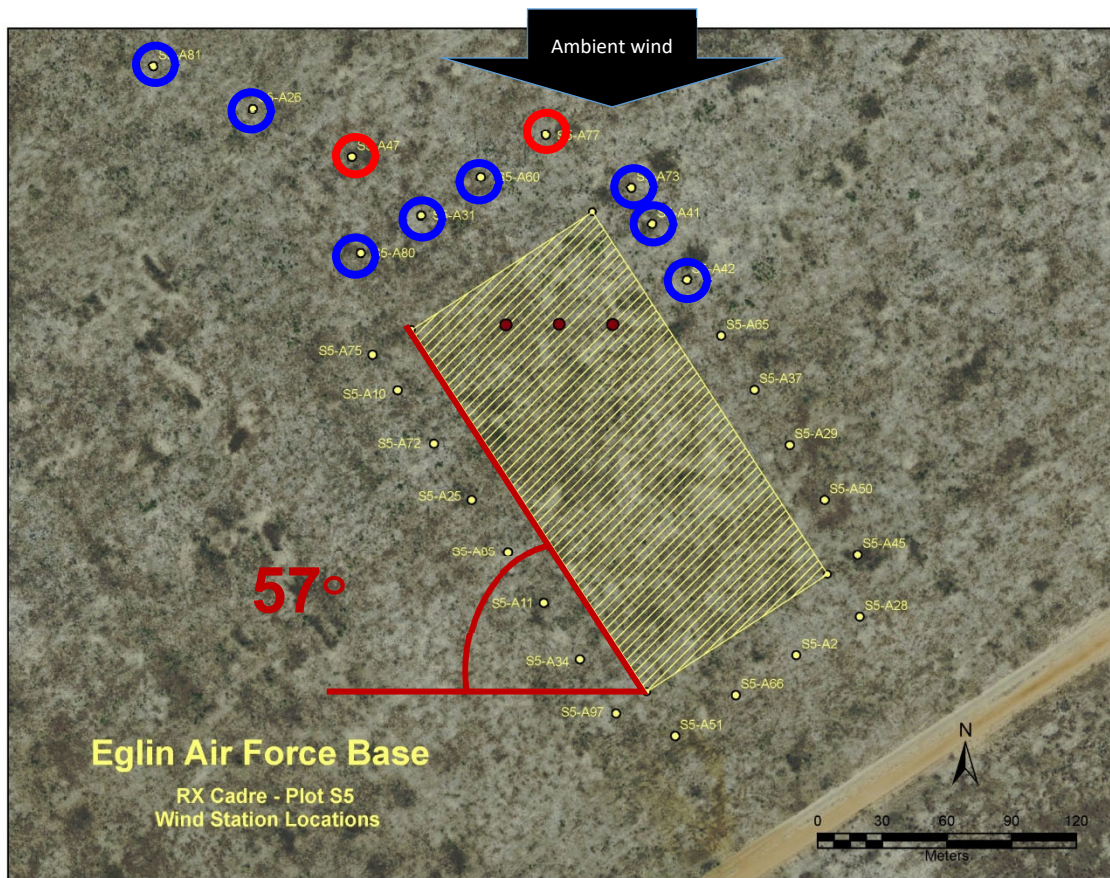


Fig. 11. Layout of the S5 plot (hashed area) with 27 anemometers shown with yellow numbered dots. The blue and red circles indicate the anemometers that were considered upwind in the context of ambient wind on the day of the burn. The three red dots indicate the center point and ends of the ignition line.

Of the 27 anemometers, 10 were considered “upwind” based on the ambient wind direction on the day of the S5 burn, shown in blue or red circles in Fig. 11. Of these 10 upwind anemometers, 2 of them (A47 and A77, shown in red circles in Fig. 11) were found to be in disagreement with the other sensors in terms of their computed wind direction, as shown in Fig. 12. For the purpose of this study, those two anemometers, which were statistical outliers, were assumed to have sensor misalignment errors and so were disregarded. It is possible that these alignment errors could be corrected, but that was outside the scope of this study.

The remaining 8 anemometers exhibited similarities in the evolution of their measured wind speed and direction (angles in degrees clockwise from due north), as shown in the bottom set of images of Fig. 12. However, there are variations in the winds between the sensors at any given point in time, reflecting spatial variability in the wind field, and the winds at all of the sensors vary with time.

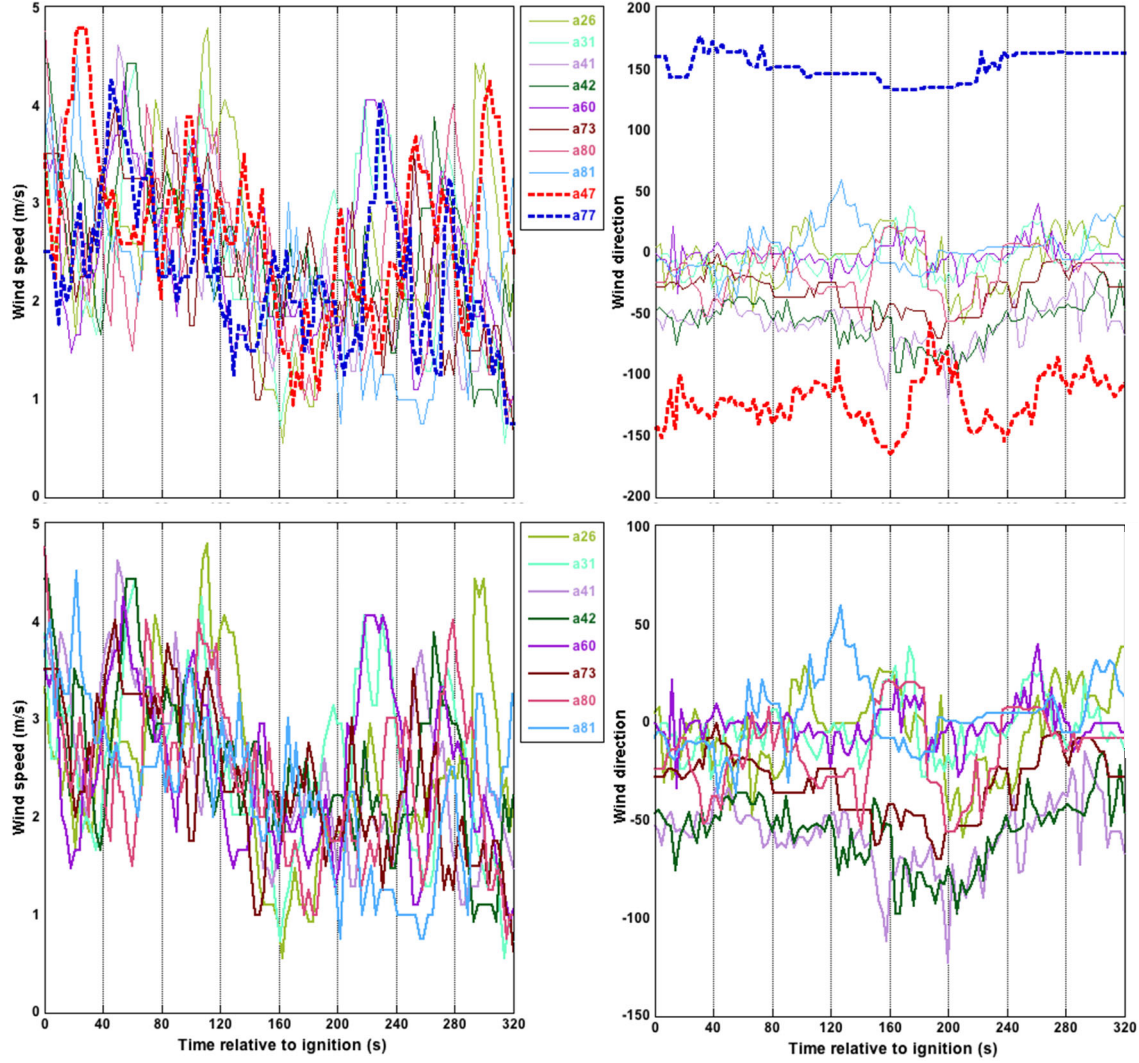


Fig. 12. Wind speed and direction measured at 3 s intervals for the 10 upwind anemometers (top row) and 8 upwind sensors that were used in the analysis (bottom row). The bold lines shown in the top two figures are data from the 2 sensors that were considered suspect in terms of wind direction since they were very different from the rest of the wind direction data from sensors upwind of the fire. These two lines correspond to the anemometers that are circled in red in Figure 11.

The wind speed, S_n , and direction, α_n , from a specific anemometer, n , at any point in time can be converted to two orthogonal velocity components, u_n (velocity west to east) and v_n (velocity south to north), using

$$u_n = -S_n \sin(\alpha_n - 147^\circ)$$

$$v_n = -S_n \cos(\alpha_n - 147^\circ)$$

The mean speed of the wind for a specific anemometer could be calculated by averaging the S_n values over the duration of the simulation to get a mean speed.

This average is equivalent to $\sqrt{2KE_n}$, where KE_n is the total kinetic energy per unit mass of air associated with motions in the horizontal direction (we do not know what the vertical motions are so they are assumed to be zero) at any point in time for sensor n . However, this methodology produces a value that is not indicative of the mean velocity or the net driving force on the fire, where directionality matters significantly. For example, a wind that is simply rotated in a circle would suggest a positive mean speed, $\sqrt{2KE_n}$, using this methodology, whereas the average wind in any direction would be zero. Instead, we compute the time-averaged u and v components, $\bar{u}_n$ and $\bar{v}_n$, and from these values compute the time-averaged wind magnitude $\bar{S}_n$ and direction $\bar{\alpha}_n$ for each anemometer.

$$\bar{S}_n = \sqrt{\bar{u}_n^2 + \bar{v}_n^2}$$

$$\bar{\alpha}_n = \text{atan}\left(\frac{\bar{u}_n}{\bar{v}_n}\right) + 147^\circ$$

The component of the instantaneous wind that is in the direction of the mean direction of the wind at anemometer n , $u_{\parallel,n}$, could be computed: $u_{\parallel\bar{\alpha}_n} = -u_n \sin(\bar{\alpha}_n) - v_n \cos(\bar{\alpha}_n)$ and a component of the wind that is perpendicular (90 degrees clockwise from mean wind direction) to the mean direction, $u_{\perp,n}$, is computed: $u_{\perp\bar{\alpha}_n} = -u_n \cos(\bar{\alpha}_n) + v_n \sin(\bar{\alpha}_n)$. However due to the manner in which we have defined the mean speed and mean angle, this calculation is not necessary as $u_{\parallel\bar{\alpha}_n} = \bar{S}_n$ and $u_{\perp\bar{\alpha}_n} = 0$

The perturbation from the time averaged mean in each of the horizontal wind components for each anemometer, u' and v' , or the perturbation in the wind magnitude and wind angle, S'_n and α'_n , can be calculated at any point in time for sensor n , using the following rules for a general quantity β_n .

$$\beta'_n = \beta_n - \bar{\beta}$$

In the case of the instantaneous wind parallel and perpendicular to the mean direction of the wind at anemometer n , $u'_{\parallel,n}$ and $u'_{\perp,n}$, are computed: $u'_{\parallel\bar{\alpha}_n} = -u'_n \sin(\bar{\alpha}_n) - v'_n \cos(\bar{\alpha}_n)$ and $u'_{\perp\bar{\alpha}_n} = -u'_n \cos(\bar{\alpha}_n) + v'_n \sin(\bar{\alpha}_n)$.

The standard deviation of a quantity β is computed as:

$$\sigma_\beta = \sqrt{\frac{\sum_{n=1,N} \beta'^2_n}{N}}$$

where N is the number of measurements taken by an anemometer during the burn period.

$(\sigma_{u_n}^2 + \sigma_{v_n}^2)/2$ is the turbulent kinetic energy associated with the horizontal motions of the air at the location of anemometer n . Statistics computed using the equations above for the 8 upwind anemometers are shown in Table 2.

Anemo- meter	Mean wind speed, $\bar{S}$, (m/s) and standard deviation, σ (m/s)	Mean wind direction, $\bar{\alpha}$, (degrees clockwise from north) and standard deviation, σ (degrees)	Standard deviation of wind $\parallel$ to mean wind direction (m/s)	Standard deviation of wind $\perp$ to mean wind direction (m/s)	Mean west-to- east velocity, $\bar{u}$, (m/s) and standard deviation, σ (m/s)	Mean south- to-north velocity, $\bar{v}$, (m/s) and standard deviation, σ (m/s)	Mean kinetic energy per mass (m ² /s ²) and turbulent kinetic energy per mass (m ² /s ²)
S5-A81	2.17	3.91	0.76	0.80	-0.15	-2.17	2.35
	0.81	18.10			0.79	0.77	0.60
S5-A26	2.35	-3.95	0.92	0.86	0.16	-2.35	2.77
	0.91	21.72			0.85	0.92	0.79
S5-A80	2.28	-15.55	0.86	0.73	0.61	-2.19	2.58
	0.84	20.05			0.76	0.83	0.64
S5-A31	2.49	-5.79	0.90	0.48	0.25	-2.48	3.11
	0.87	14.06			0.52	0.87	0.52
S5-A60	2.47	-1.26	0.86	0.38	0.05	-2.47	3.05
	0.85	10.52			0.39	0.86	0.44
S5-A73	2.29	-29.66	0.78	0.62	1.13	-1.99	2.62
	0.78	16.16			0.56	0.83	0.50
S5-A41	2.43	-56.24	0.85	0.62	2.02	-1.35	2.95
	0.81	18.23			0.64	0.84	0.56
S5-A42	2.44	-54.66	0.79	0.69	1.99	-1.41	2.97
	0.78	17.49			0.60	0.86	0.55

Table 2. Statistics for the 8 upwind anemometers from the S5 burn that were used to initialize winds in the FIRETEC simulations.

In order to use the measured data to generate initial and boundary condition winds for the simulations of the S5 burn, assumptions must be made about the correlation between the

measured wind signals and the winds throughout the computational domain at the start of the simulations and at the boundaries for the duration of the simulations. Unfortunately, the domain boundaries cannot be placed at the location of the anemometers that ring the burn plot because this would allow interaction between the domain boundaries and fire-induced wind circulations. In order to prevent such interactions, the domain boundaries, shown with a black line (Fig. 19, page 40) were placed 150 m from the burn plot in the x direction (direction of the short dimension of the S5 plot) and 200 m from the burn plot in the y direction (direction of the long dimension of the S5 plot). This put the boundaries at least 130 m from the ring of anemometers that were placed around the burn plot. It was necessary to spatially extrapolate the anemometer data to prescribe the dynamic winds at the boundaries of the computational domain, including winds aloft. Challenges of this process include:

- 1) Capturing adequate representation of the spatial variability of the winds
- 2) Representing the dynamic winds at the boundaries with realistic temporal fluctuations including the dynamic wind events that influence fire behavior within the S5 plot
- 3) Using the 3.3 m high anemometer data to estimate winds at higher altitudes at the boundaries

Several different basic techniques were tested for prescribing the velocities throughout the domain at the onset of the simulations and at the boundaries, including: a) using wind components from a specific anemometer, n , (u_n and v_n) to prescribe the winds, b) simple averaging of the 8 upstream anemometer measurements U_8 and V_8 , c) using averages of 4 or 5 anemometer subsets of the upstream sensors, U_4 , V_4 , U_5 and V_5 , and d) using a nearest neighbor weighting algorithm to blend the 8 upstream anemometers to get U_{8nnw} and V_{8nnw} to prescribe the boundary points based on proximity to the various sensors. The values U_{8nnw} and V_{8nnw} are computed according to:

$$U_{8nnw}(x, y) = \frac{\sum_{n=1,8} u_n * \sqrt{(x - x_{sensor,n})^2 + (y - y_{sensor,n})^2}}{\sum_{n=1,8} \sqrt{(x - x_{sensor,n})^2 + (y - y_{sensor,n})^2}}$$

$$V_{8nnw}(x, y) = \frac{\sum_{n=1,8} v_n * \sqrt{(x - x_{sensor,n})^2 + (y - y_{sensor,n})^2}}{\sum_{n=1,8} \sqrt{(x - x_{sensor,n})^2 + (y - y_{sensor,n})^2}}$$

where $x_{sensor,n}$ and $y_{sensor,n}$ describe the location of sensor n and x and y are the location of a FIRETEC cell where the velocity is being specified. In order to allow comparison between the 8NN simulations and the other simulations, mean wind velocities for the 8NN simulations were computed by averaging the velocities at 15 evenly spaced points along the ignition line (computed with the nearest neighbor algorithm shown above) for the 320 seconds after the start of the ignition process.

Two different approaches were tested for specifying the velocities over the remaining vertical extent of the domain initially and dynamically over the duration of the simulations. The initial approach used the prescribed initial or boundary 3.3 m-high velocity, (u_0, v_0) at any x, y position at a given point in time to specify a logarithmic vertical profile using the equations:

$$u(z) = \frac{u_0}{.4} \left[\ln \frac{z}{.1} \right]$$

$$v(z) = \frac{v_0}{.4} \left[\ln \frac{z}{.1} \right]$$

After discovering problems with this approach related to the introduction of unrealistic cross-stream vorticity due to the dynamics of the log profiles aloft, a second treatment was tested. This second approach blended the rapidly varying surface winds with steady winds aloft. For this method a mean wind vertical profile was calculated using

$$u_{aloft}(z) = \frac{u_{avg}}{.4} \left[\ln \frac{z}{.1} \right]$$

$$v_{aloft}(z) = \frac{v_{avg}}{.4} \left[\ln \frac{z}{.1} \right]$$

u_{avg} and v_{avg} are 10 min average u and v wind components (from 3 min prior to ignition until 7 minutes after ignition started) computed by averaging all 8 upwind sensors over this time period. These two profiles were blended using an exponential decay weighting such that near the ground the velocities matched measured values and aloft the values matched the mean value.

This methodology is reasonable due to the fact that the dominant length scales of the atmospheric motions were expected to be finer near the ground as compared to higher above the surface; thus, the high frequency perturbations would be less significant compared to the mean wind with height. Additionally, details of the perturbations are not known higher above the ground, and this approach provided a smooth transition between the measured dynamic and heterogeneous velocity field near the ground and winds aloft.

Ten simulations, summarized in Table 3, were performed using a computational domain with a horizontal extent of 600 m x 400 m and a vertical extent of 615 m.

Simulation name	Surface wind specification	Fuels
A80	Anemometer S5-A80	Heterogeneous
A31	Anemometer S5-A31	Heterogeneous
A60	Anemometer S5-A60	Heterogeneous
A73	Anemometer S5-A73	Heterogeneous
A41	Anemometer S5-A41	Heterogeneous
4S_avg	4-sensor average	Heterogeneous
5S_avg	5-sensor average	Heterogeneous
8S_avg	8-sensor average	Heterogeneous
8NN- H	Nearest neighbor	Heterogeneous
8NN- U	Nearest neighbor	*Uniform (averaged)

Table 3. Input parameters for 10 simulations of the S5 burn described below. *Uniform fuels description included in 5.2.2.

5.2.2 S5 Fuels Characterization

Prior to each RxCADRE campaign in 2008, 2011, and 2012, fuels were characterized in experimental burn units using customized fuel sampling designs that varied by year. Variables measured included loading (tons/acre), height, and % cover of shrubs, grasses, and forbs, woody biomass loading by size class, litter depth and loading, duff depth and loading, cone counts and loading. In 2012, sampling was more intensive. For each of the six small block replicates (100m x 200m blocks), including the S5 block used for this demonstration, 25 – 1 m² plots were sampled.

The S5 plot was perceived to be a homogenous mixture of fuels from a macro perspective (at 100s of meters to kilometer scales). However, like the other small-block replicates the fuels were quite heterogeneous at scales smaller than 10 m. Because the fuel's heterogeneity scales could be resolved by the model, and the variation in types of fuel were significant in terms of potential fire behavior (e.g. woody goldenrod does not carry fire well while tall grass burns readily), efforts were made to represent the heterogeneous distribution of fuels that would be combusting in the S5 plot. For these reasons, a new method for developing fuel beds for physics-based models such as FIRETEC was developed by the project team.

Meter-scale regions of relatively heterogeneous fuel within the S5 plot were identified during site visits in November, 2013. These regions were recorded with GPS coordinates and photos, which also documented their spatial relationship with regards to other fuel types. Seven major fuel types were identified for the S5 plot: short grass, tall grass, palmetto, little blue stem, woody goldenrod, clay road, and bare ground or sand. The road and bare ground were classified separately even though the road is bare ground because the clay added into the road surface gives it a different appearance, so it could be used for visual reference.

High-resolution aerial photography (15 cm resolution) shown in Fig. 13 (courtesy of Eglin Air Force Base Geointegration Office) was used. This visible spectrum imagery illustrates the vegetation heterogeneity through different colors. The fact that the patterns in the photograph, which was taken in 2010, seemed to be very similar to the patterns observed during a site visit in 2013, and the fact that most of the plant species present on site are perennial, suggests that they were approximately the same as the fuel classification patterns present during the 2012 burn. Thus, the imagery and 2013 ground-truth/site-observations were assumed to be representative of the types of fuels and patterns that were present at the time of the burn.

Examples of each of the seven dominant fuel types identified during the site visit were located in the photograph and used to “train” a commercially available adaptive feature extraction software package, Genie Pro 2.4 (Copyright 2007-2012 Observera, Inc.), to classify the remaining portions (approximately 98%) of the image, as seen in Fig. 13. This supervised classification was accomplished through an iterative process where a few areas with known fuel types were used to guide the initial GENIE-based classification, and then regions classified by GENIE were compared to known fuel types in the image to validate the classification pattern. In locations where the classification was incorrect, GENIE was “trained” again based on additional known

fuels and then used to reclassify the entire image until the classification showed no notable errors as compared to the imagery. Site experts then verified that they felt that the classification had captured the major features of the fuel patterns in the S5 plot. The 7 identified fuel classes were:

- *Palmetto (PA)*
- *Tall Grass (TG)*
- *Short Grass (SG)*
- *Little Blue Stem (LBS)*
- *Woody Golden Rod (WGR)*
- *Bare Ground (BG)*Field verification
- Road

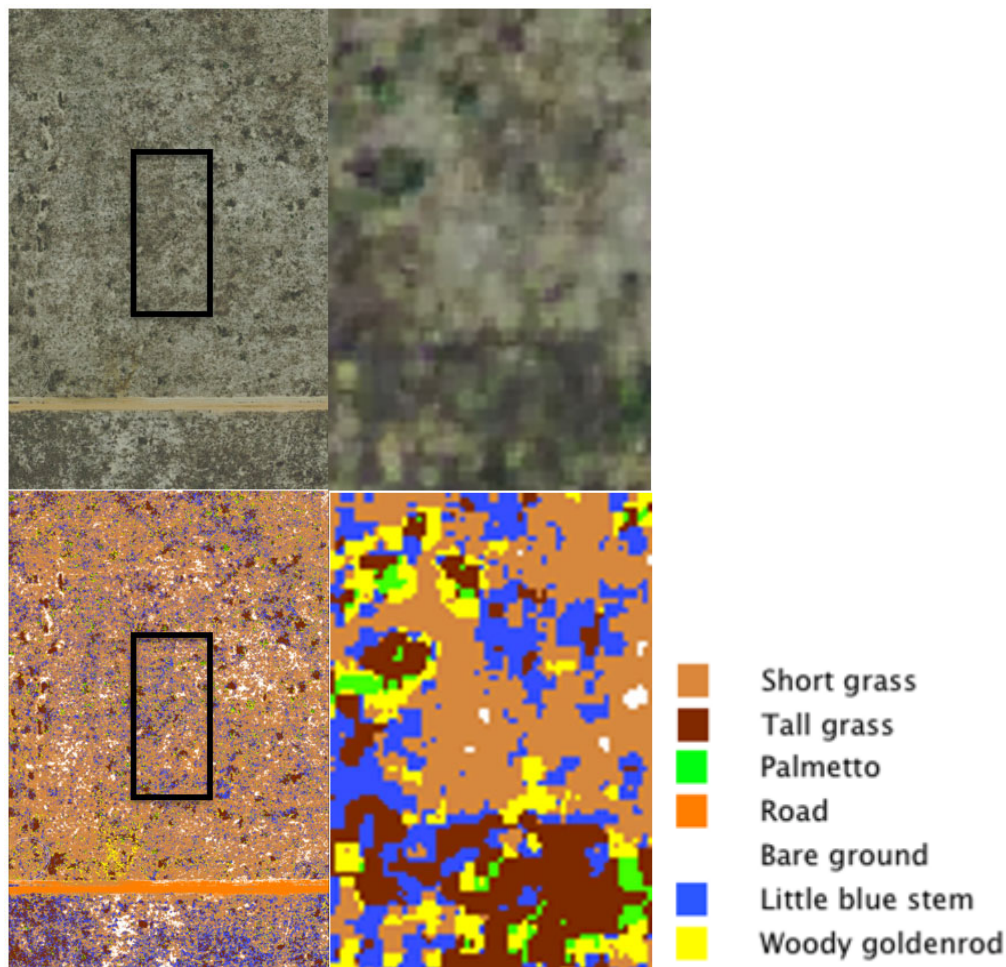


Fig. 13. Fuel class verification/comparison imagery. Left side shows high-resolution (0.15 m) images of the landscape (400 m by 600 m) around S5. S5 boundary is shown in black. Images on the right are zoomed (10 m x 15 m) to show detail near the center of S5. Images in the top row are raw visual spectrum imagery and GENIE fuels classifications on bottom (Color key: light brown = short grass; dark brown = tall grass; light green = palmetto; blue = little blue stem; yellow = woody goldenrod; orange = road; white = bare ground or sand.). Image courtesy of Eglin Air Force Base Geointegration Office.

These specific fuel classes were identified on 20 site locations in November 2013 using GPS and orientation referenced to a fixed tower (Figure 14). The 20 locations were on Eglin Test Area B-70 in an unburned area near the S5 block.

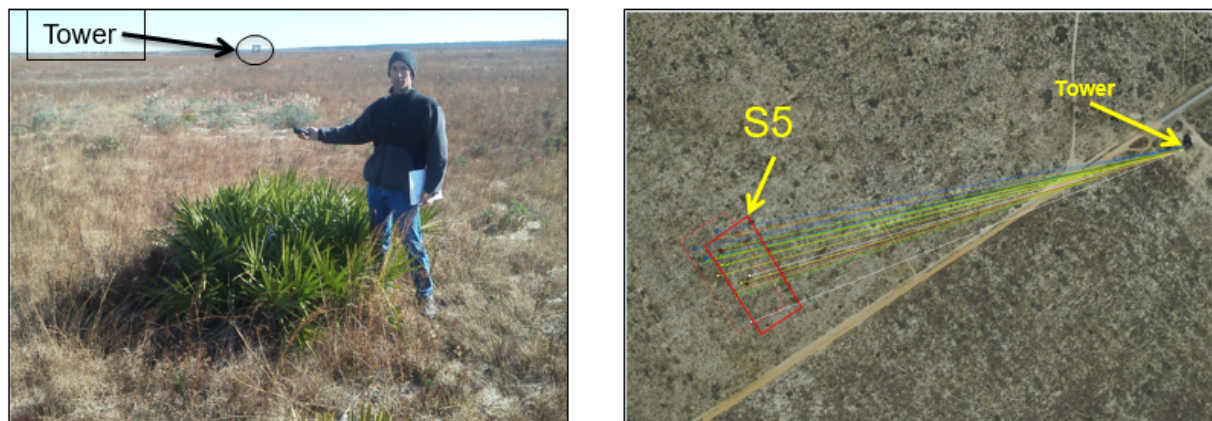


Fig. 14. Fuel class verification was carried out by field sampling comparison with high resolution imagery. Precise locations of specific fuels were triangulated via GPS and location relative to an Eglin tower.

With the heterogeneous S5 plot fuels characterized in terms of type, the next step was to associate fuel properties with each type. Destructive sampling had been performed (Ottmar *et al.* 2016) just prior to the burns in 2012. The fuel load, height and surface-area-per-unit-volume captured from the destructive sampling plots were used to associate respective values with each of the fuel classes mentioned above. Although fuel moisture information was also collected through the destructive sampling, the live and dead moisture fractions were not separately recorded. In this fuel complex, it was found to be inappropriate to use mass weighted fuel moistures for the fuel in each cell because the moisture levels of the dead fuel were much lower than the live fuels and thus carried the fire. Therefore, the fire front was assumed to consume the dry fuels while the live fuels would smolder behind the fire front and not contribute to fire spread. With this assumption, the mass of the fuels and the moisture levels were made consistent with the dry fuels.

With fuel properties assigned to each 15 cm pixel of the high resolution image, the pixels could be combined to generate average properties over the FIRETEC grid cells of 2 m x 2 m, as shown in Fig. 15 and 16 for fuel density, moisture and height. As indicated in Table 3, in order to assess the potential magnitude of the impact of fuel heterogeneity on the fire behavior we ran one simulation, 8NN-U, with homogenized/uniform fuel over the entire computational domain. The homogenized fuelbed was created by applying the average of the loads and the heights over the domain.

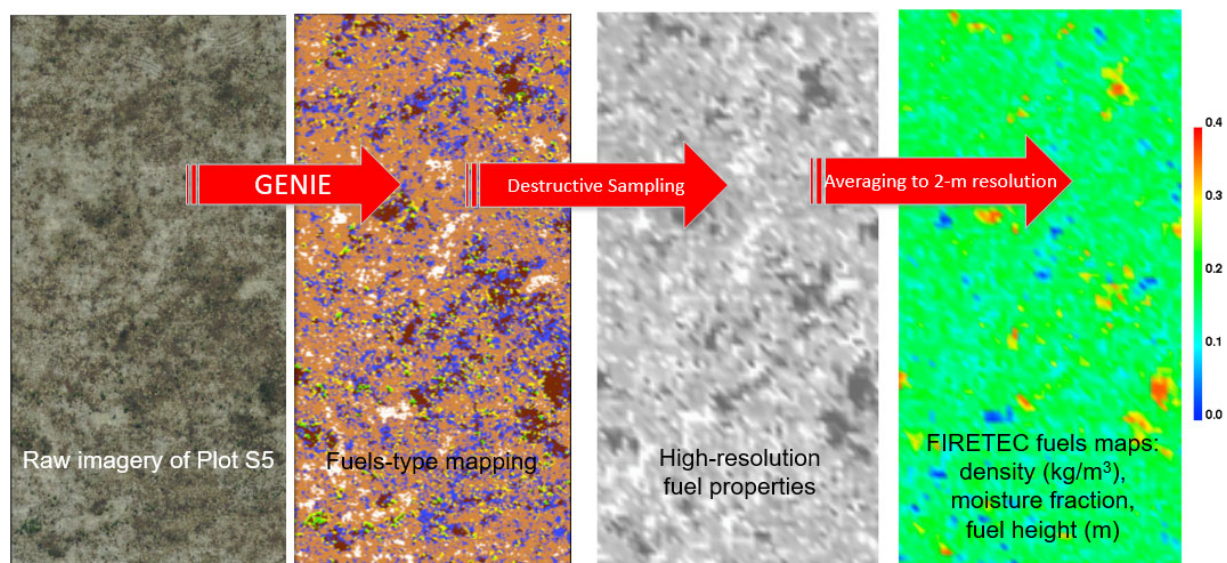


Fig. 15. Flow chart for processing of the raw 0.15 m imagery of the S5 plot through fuels characterization mapping, associating fuel properties from destructive sampling and finally building fuel data such as fuel density at 2 m x 2 m resolution for use in FIRETEC.

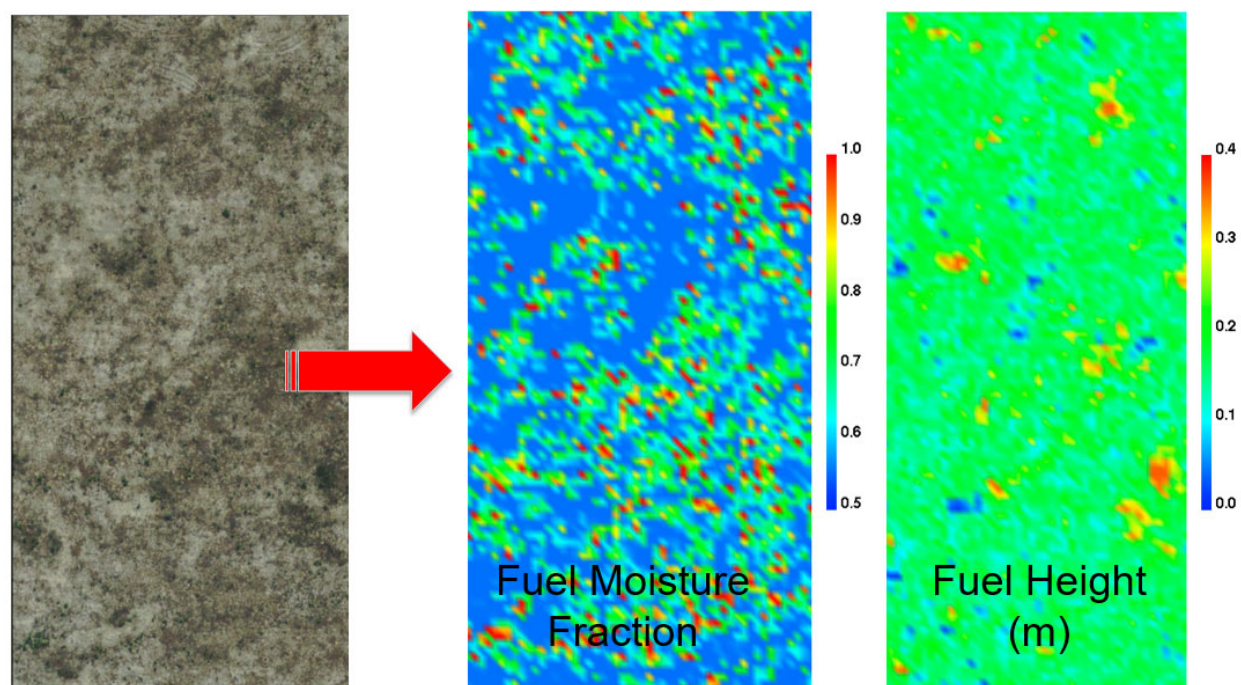


Fig. 16. A process similar to that illustrated in Figure 15 was developed for modeling fuel moisture and fuel height, which are required FIRETEC inputs.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY AND METHODOLOGY COMPONENTS

Evaluation of Performance Objective 1 focused on utilizing 2012 RxCADRE datasets for the S5 burn block to further validate FIRETEC's performance in predicting wind fields, fire spread, heat flux, and fire behavior for low intensity surface fires in longleaf pine sandhills fuelbeds. Of all three years that RxCADRE took place at Eglin (Fig. 17), the most complete dataset for fuels, wind field, heat release, and fire behavior data within a formal sampling design was produced by the 2012 RxCADRE dataset. For this reason, RxCADRE 2012 data was chosen for the comparison against results of FIRETEC predictions of fine-scale wind fields, heat flux, and fire behavior. All 2012 RxCADRE burns occurred in late October/early November. Based observed fire behavior accounts and records, it was clear that fire behavior between the six small (100 x 200 meter) burn block replicates was not consistent as they were exposed to different winds and fuels, but that all of them displayed low-intensity and often very marginal fire behavior. The challenge for modeling fire activity under low and variable wind and light and patch fuels is that exhibits very heterogeneous and transient fire behavior if it persists and in many locations goes out based on local (time and space) details of the winds and fuels. In the text below these kinds of conditions are referred to as marginal and they are close to the boundary between conditions fires can spread vs. where they self-extinguish. Because Objective 1 was focused on comparing observations of low-intensity fire to a deterministic fire to a fire behavior predicted by a deterministic model, we chose to use the S5 Burn Block (Fig. 18), which exhibited the most consistent fire spread. In hindsight, this was a fortunate choice because the complications described below for simulating marginal fire would have been expected to be much worse for the other small block burns, which were even less consistent.

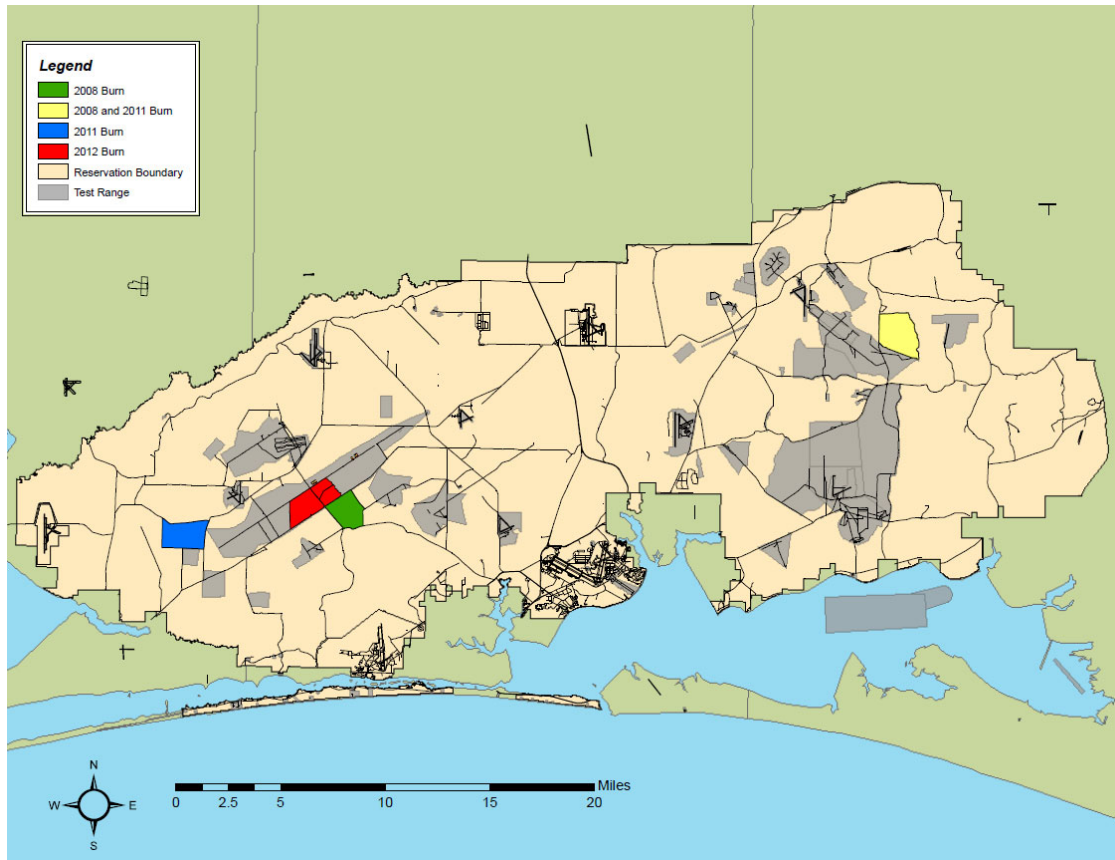


Fig. 17. RxCADRE 2008, 2011, and 2012 burn unit locations at Eglin AFB, FL.

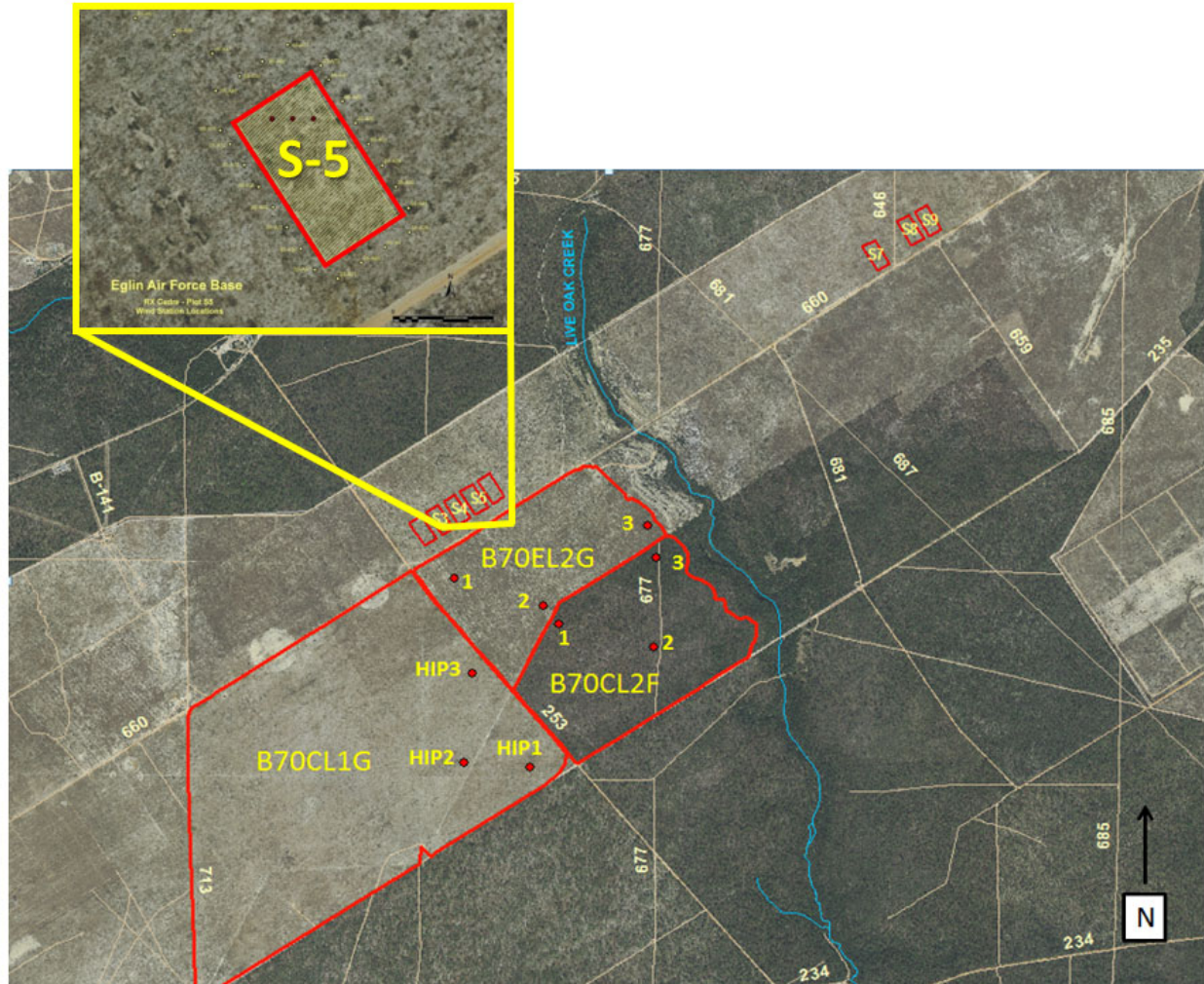


Fig. 18. Zoom view showing location of S5 in relation to other RxCADRE 2012 burn units (outlined in red) on Test Area B-70, Eglin AFB, FL.

The computational grid used for FIRETEC simulations of the S5 burn block was 400m by 600m as illustrated in Figure 19. In this figure, the burn area is indicated with yellow hatch marks. Yellow dots indicate anemometer locations and the three red dots indicate where the line of fire was ignited for the actual burn. The ignition line was established by moving two individuals with drip torches in opposite directions from the center of the ignition to the two ends of the line; documented locations of these points are marked by the three red dots in Figures 19 below. The speed at which the igniters traveled was reported to be 1.34 m/s (3 mph) in field experiment documents. The result of this procedure is an ignition line that grows from its center toward its ends.

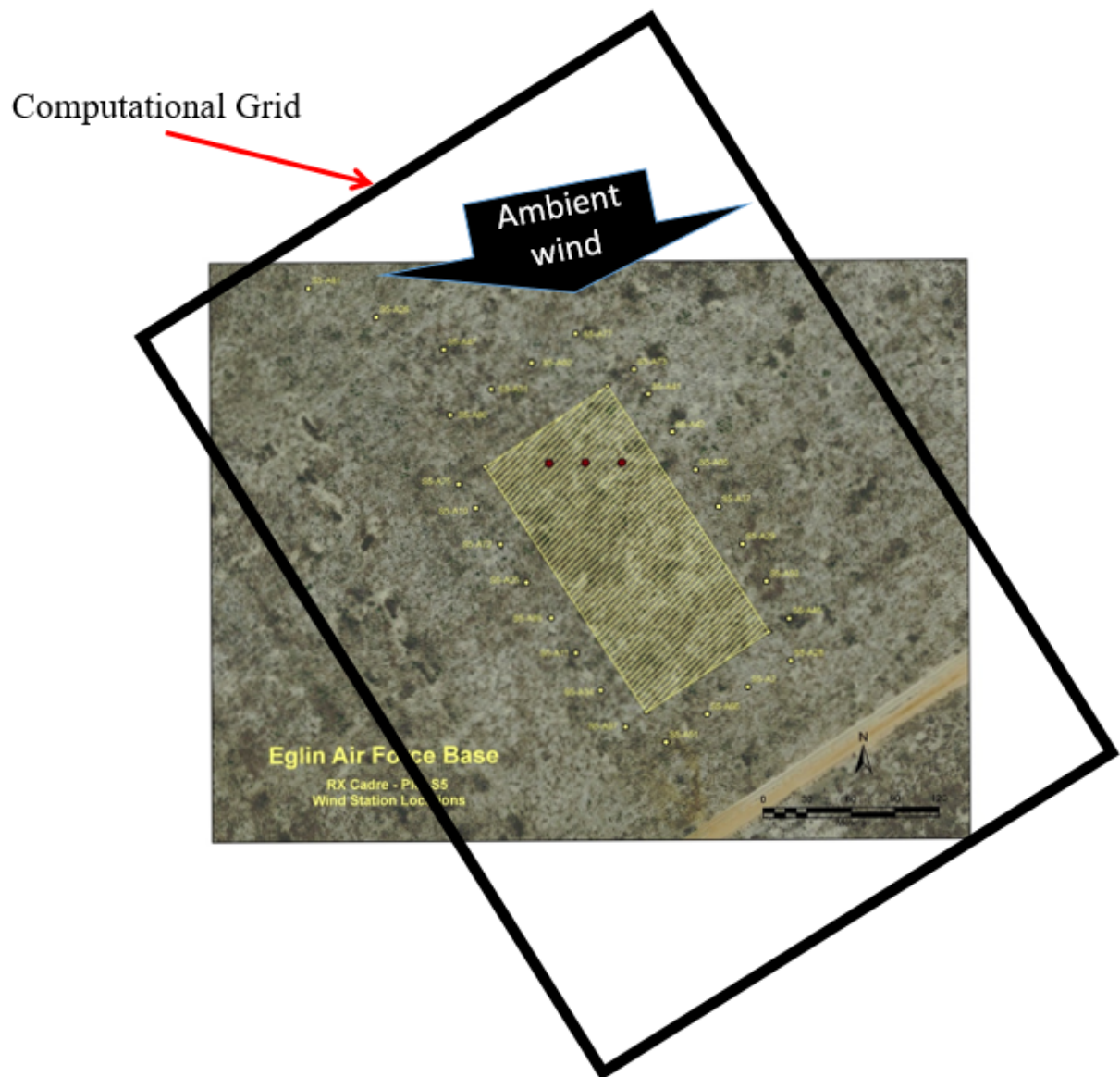


Fig. 19. FIRETEC computation grid, outlined in black (400m by 600m), used for S5 simulations. Yellow dots indicate anemometer locations. Red dots indicate location of ignition line.

6.0 PERFORMANCE ASSESSMENT

6.1 Performance Objective 1. Further validate FIRETEC's ability to simulate representative coupled fire/atmosphere behavior

Successful completion of Performance Objective 1 was accomplished by a comparison of RxCADRE data from the 2012 RxCADRE S5 block to FIRETEC simulations using weather and fuels data described above. These simulations ultimately showed that FIRETEC was capable of simulating fires with the same spread characteristics as observed in the field experiments. However, the numerical explorations also illustrated that significant challenges associated with using a limited set of observations to drive simulation of actual fires under marginal fire conditions, especially fires where the local fluctuations in winds and fuels are very significant compared to the respective mean values.

It is important to understand that coupled fire/atmosphere simulations are difficult to compare to field measurement using standard statistical tests on multiple fire replicates because replication of burns is nearly impossible in the field. Even when ignition patterns are similar and plot layouts are similar, the wind conditions and timing of the gusts with respect to the ignition will not be the same and the fuels will not be identical. In similar model validation studies where deterministic fire behavior models have been compared with observation for specific fires, model performance is evaluated as a success if model outputs fall within the range of values observed in the field (Linn and Cunningham 2005, Mell et al. 2007, Achtemeier et al. 2012, Linn et al. 2012, Mueller et al. 2014, Terrei et al. 2019) or within 20-30% of integrated values such as spread rate. Hoffman et al. (2016) compared a wide range of simulations with two such deterministic fire behavior models (FIRETEC and WFDS) to a published data set of forest fire observations in a statistical manner. Hoffman's conclusions were that although the range of simulated results compared to well with the envelope of observations it was very challenging to compare the specific observed fires to simulations because there the records of environmental associated with the observed fires (winds and fuels etc.) did not include sufficient detail to fully prescribe the inputs for the model simulations. If the range of model output values based on realistic perturbations of unconstrained fire environment variables includes the values of a given response variable as observed in the field, then the model is considered to have performed well in prediction for that response variable. In general, the more field environment data that is available or the lower the natural variation is in the environmental conditions with respect to their mean, the tighter the simulation output range is expected to be. Validation of FIRETEC's ability to capture realistic coupled fire/atmosphere behavior was partially evaluated on prediction of fire perimeter acceleration/deceleration and directionality in response to wind shifts as measured in RxCADRE.

6.1.1 Simulations

The downwind spread rate of the simulated fires is computed based on the farthest downwind travel distance in the direction of the simulation-specific mean wind. The mean wind speed was computed by averaging for 320 s after ignition. Because the direction of the wind is different for each of the simulations, the distance traveled in each of the simulations is computed in different directions. For each point on the fire perimeter, the distance traveled is computed by drawing a line from the perimeter point in the direction parallel to the mean wind. The distance from this perimeter point to the intersection of

the wind direction line and the ignition line is taken to be the downwind spread distance. The perimeter of the simulated burned area at 320 s was estimated based on the consumption of the fine fuel at that time. For comparison sake, the spread rates were also computed using the wind direction from the average of all 8 upwind sensors. For the purpose of this manuscript, a fuel consumption of 25% was used to change the designation of a particular computational cell from unburned to burned. With this distinction we can compute burned area as a function of time.

Macroscale metrics from each of the simulations are provided in Table 4 below.

Simulation	Mean wind speed, $\bar{S}$ (m/s)	Mean wind direction, $\bar{\alpha}$ (degrees clockwise from north)	Spread rate (ROS) in direction of specific mean wind (m/s)	Spread rate (ROS) in direction of mean wind across all 8 sensors	Area burned at 320 s after ignition (m ²)
A80	2.28	-15.55	0.279	0.278	2676
A31	2.49	-5.79	0.359	0.347	4108
A60	2.47	-1.26	0.504	0.476	5424
A73	2.29	-29.66	0.324	0.320	3592
A41	2.43	-56.24	0.118	0.096	1212
4S_avg	2.34	-12.61	0.380	0.377	4260
5S_avg	2.25	-21.09	0.420	0.420	4404
8S_avg	2.19	-20.34	0.322	0.322	3452
8NN-H	2.20	-22.68	0.413	0.413	3444
8NN-U	2.20	-22.68	0.531	0.531	5540

Table 4. Spread rates for S5 simulations, as well as the wind speed and direction used to compute them. Mean wind speed and direction from single anemometers are from Table 2. Spatially averaged values for the instantaneous velocity components, $\bar{u}_l$ and $\bar{v}_l$, are computed through a simple average among a set of l anemometers (we used $l=4, 5$, and 8). 4S_avg mean winds are averaged from anemometers S5-A31, S5-A60, S5-A73, and S5-A80. 5S_avg mean winds are averaged from anemometers S5-A31, S5-A41, S5-A60, S5-A73, and S5-A80. 8S_avg mean winds are averaged from anemometers S5-A26, S5-A31, S5-A41, S5-A42, S5-A60, S5-A73, S5-A80, and S5-A81. Nearest neighbor algorithm derived winds for both heterogeneous and uniform fuels were also simulated.

The fire perimeters at 320s after ignition started in the context of the burn plot (not the entire simulation domain) from the 5 simulations with wind fields based on the time series from a single anemometer are shown in Figure 20. It is important to note that these images have been rotated compared to the plot layout shown in Figure 19 since this was the way the simulations were set up. For reference, north is marked with the black arrow and mean wind direction and magnitude is marked with the purple vector. Figure 20 illustrates the significant qualitative

variation between these 5 burn perimeters, which is associated with the variation in the wind speeds and directions at the various anemometers. For example, the winds recorded at A41 were between 27, 41, 50 and 55 degrees counterclockwise from sensors A73, A80, A31 and A60 respectively. Anemometer locations are illustrated in Figure 11.

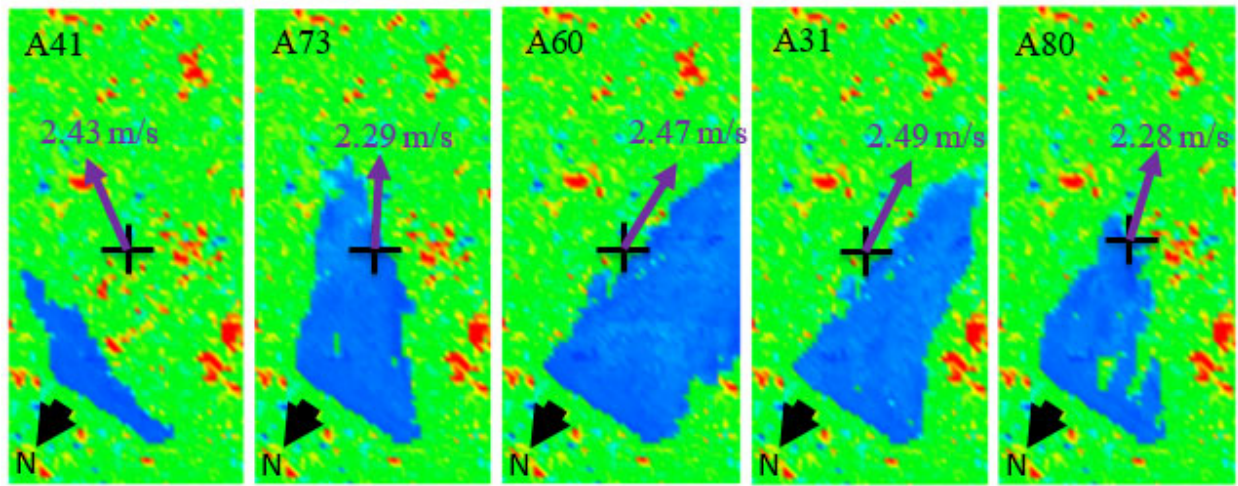


Figure 20. Fire perimeters from FIRETEC simulations at 320s after ignition initialized with wind series from individual anemometers (from left to right) A41, A73, A60, A31, and A80. These fire perimeters are shown on the S5 burn plot domain, not the entire computational grid.

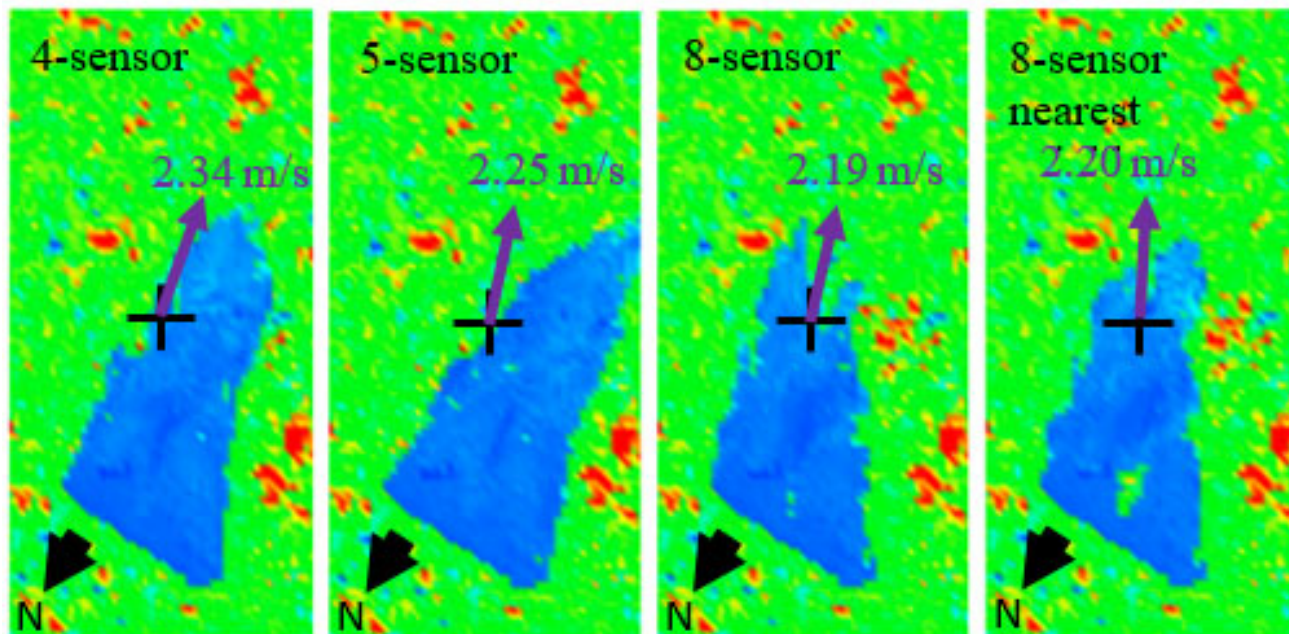


Figure 21. Fire perimeters from FIRETEC simulations at 320s after ignition initialized with averaged wind series. 4-sensor average winds are generated from anemometers S5-A31, S5-A60, S5-A73, and S5-A80. 5-sensor average winds are generated from anemometers S5-A31, S5-A41, S5-A60, S5-A73, and S5-A80. 8-sensor average and 8-sensor nearest neighbor winds are generated from anemometers S5-A26, S5-A31, S5-A41, S5-A42, S5-A60, S5-A73, S5-A80, and S5-A81. These fire perimeters are shown on the S5 burn plot domain, not the entire computational grid.

The burn perimeters for the 4S_avg, 5S_avg, 8S_avg, NN-H simulations at 320s are shown in Figure 621. There are still differences between the fire perimeters using the various composite wind conditions, but the variations are less than those shown in Figure 5 with the five individual sensors.

Table 2 describes the range of wind speeds and directions in a variety of ways for each of the 8 anemometers as well as the variations in these values in terms of the standard deviations. The wind speeds measured at these 8 anemometers ranged from 2.17 m/s to 2.49 m/s (~15% variation between the sensors and a standard deviation of .11 m/s). However, the speeds individually do not convey the presence of the potentially significant temporal or spatial variation in the winds.

Temporal wind variation

The standard deviation of the wind speeds listed in the first column of Table 2, which ranged from .78 m/s to .91 m/s with a mean of .83 m/s, is indicative of the temporal wind variation at individual sensors. The fact that the standard deviation of the wind speeds at individual anemometers is significantly larger than the standard deviation of the mean wind speeds of the 8

upwind anemometers, .11 m/s, suggests the importance of the local rapid temporal wind fluctuations compared to larger-scale heterogeneities ($>\sim 100$ m) that would induce persistent wind speed differences amongst the anemometer locations. Such larger-scale heterogeneities could have been caused by spatial patterns in the differences in upwind vegetation (i.e. forest edges or differences in land use), but in the case of S5 the upwind surface conditions were fairly similar in terms of land surface changes on scales of ~ 100 m.

The standard deviation for the wind components parallel to the mean wind speed, which are in general slightly higher than the standard deviation for the wind speed, are indicative of the local gustiness of the wind in the direction of spread. The fact that these values range from 32% to 39% of wind speed in this direction illustrates that the range of fluctuation is on the same order of magnitude as the mean wind speed (for example, if we assume a Gaussian distribution of wind fluctuations at anemometer A81, only 68% of the winds will be within a 1.52 m/s range centered at the mean wind speed of 2.17.) This is consistent with the magnitude of the swings seen on the left side of Fig. 20.

The standard deviation of the wind components perpendicular to the mean wind angle range from .38 m/s to .86 m/s, which are 15% to 37% of the mean wind. These lateral wind fluctuations are responsible for the changes in local instantaneous wind directions. The fact that the various anemometers do not see the same lateral fluctuations at the same time (and the time average of the lateral fluctuations varies between the sensors) results in the variation in angle between the 8 anemometers. This is a significant amount of crossflow variability, and is indicative of the fact that the timing of ignition or position of an anemometer in space could have a significant impact on the mean angle of the wind.

The standard deviation of the wind directions, which reflects the local crosswind fluctuations described above, ranges from 10.52 to 21.72 degrees. These are indicative of the local directional variation that a single anemometer showed during the S5 burn. This variation of measured wind directions at the individual anemometers is of the same order of magnitude as the standard deviation of the mean wind directions across the array, 24 degrees (comparing the wind orientation across the array of anemometers). This variation in wind directions across the upwind sensor array could be a result of the anemometers being placed at different spatio-temporal locations with respect to coherent wind fluctuations with time scales on the order of 320s or spatial scales on the order of 100 to 200 m.

The local temporal variation is also indicated by the ratio of the turbulent kinetic energy per unit mass compared to the mean kinetic energy per unit mass (the ratio of the numbers in the last column of Table 1), which range from 14% to 25%. The ratio of the wind speed perpendicular to the simulation-specific mean wind to the wind speed in the direction of the simulation-specific mean wind is another indicator of the local temporal variation at the anemometers.

Spatial wind variation

The range of angles for the mean winds across the 8 individual sensors, 60.15 degrees, and the associated variation in the $\bar{u}$ and $\bar{v}$ wind components illustrates the substantial spatial variation in the wind directions. It is worth noting the trend in directions with the spatial location of the sensors. As illustrated in Fig. 20, A73 and A41) which are farther east of the fireline show wind

directions that have stronger westerly components (more negative wind angles). The range drops to approximately 55 degrees when we consider only the 5 upwind anemometers that are most directly upwind of the fire.

The range of wind directions for the eight anemometers illustrates the significance of the spatial variability of the winds relative to a site-wide mean wind. If the site-wide mean wind had been higher, the same magnitude of fluctuation in the winds would not have resulted in such a wide angular range for the individual anemometer since the angular deviation from the site mean β goes with $\sin^{-1}$ (cross stream perturbation/mean wind speed). The impact of fluctuations perpendicular to the mean wind decreases as large-scale site-wide mean wind increases.

In Table 2, the mean and standard deviation for the u and v velocity components reflect the fact that anemometers on the western portion of the upwind anemometer array (A81, A26, A80, A31, and A60) have mean flow that is predominantly out of the north (mean u components have much smaller magnitudes than the v components). As was shown by wind direction trends, velocity components also reflect that the wind directions farther to the east (A73, A41, and A42) have a more significant westerly component during this time period. This is indicative of a larger-scale ($> \sim 100$ m) structure in the flow that is passing through the anemometer array at the time of the burn, giving a macroscale directional trend. This directional trend is different from smaller-scale wind field fluctuations shown by the components at various individual anemometers (what many will call turbulence) that are much more horizontally isotropic, with both u and v standard deviations ranging from .52 m/s to .85 m/s and .77 m/s and .86 m/s, respectively.

Mean wind speed and direction are included in Table 4 for the five single anemometer simulations as well as the composite simulations in order to provide context for the fire spread. The mean wind speeds of the composite simulations are mostly slower than those of the single anemometers. This reflects the fact that these composite wind speeds include the sum of counteracting instantaneous component contributions from anemometers with different mean directions. The measured mean wind directions for the 5 upwind anemometers listed in Table 4 range over nearly 55 degrees (-1.26 degrees to -56.24 degrees clockwise from north) during the first 320 seconds after ignition at locations within 140 meters of one another and between 50 m and 120 m from any point on the ignition line. The winds in the composite simulations have a much smaller range, -12.61 degrees to -26.5 degrees, which is relatively central compared to the range of the individual anemometers. This smaller range is also indicative of the blending that occurs when counteracting wind components from various anemometers are combined together.

Fire spread.

Table 4 describes the rates of spread (ROS) and area burned in simulations using the five anemometers that are immediately upwind of the fire. Table 4 also includes this data for five simulations with wind speeds made up of composites of winds from subsets of the eight anemometers listed in Table 2.

The ROS values for the five single-anemometer simulations in the direction of the mean wind for each specific simulation are between 0.118 m/s to 0.504 m/s, a range of variation of 327%. The breadth of this range shows much wider variation than that of the mean wind speed for those same simulations, 9%. Spread rates are plotted as a function of simulation specific wind speed in

Fig. 22a and 22b for the single-anemometer and composite wind simulations. Figure 22a illustrates that there is no clear spatial trend connecting spatial locations of the sensors and spread rates, for example moving from west to east (A80 to A41) the spread rates do not monotonically rise or fall. Figure 22a also illustrates that the spread rate of the composite simulations are more tightly grouped in value than those of the single anemometer simulations. The plot in Figure 22b illustrates that wind speed alone does not explain the variation in rate of spread for the five single-anemometer simulations or the composite simulations. This wide range in the rates of spread is partially due to the fact that not only does the magnitude of the wind affect the net rate of spread, but the orientation of the ignition line with respect to the wind direction matters as well. Past observations and numerical explorations (Cheney et al. 1993, Linn et al. 2005, Pimont et al. 2012, Canfield et al. 2014) have noted that the length of the fire line impacts the spread rate when the line is perpendicular to the mean wind. When the projection of the line perpendicular to the wind is shorter, the spread rate would be less. For example, the wind at sensor A41 is much closer to being parallel to the ignition line than for any of the other sensors. Thus, the projection of the ignition line perpendicular to the wind is much smaller, as is the ROS even though the mean wind speed for sensor A41 is the second highest amongst the 5 anemometers shown in Tables 3 and 4.

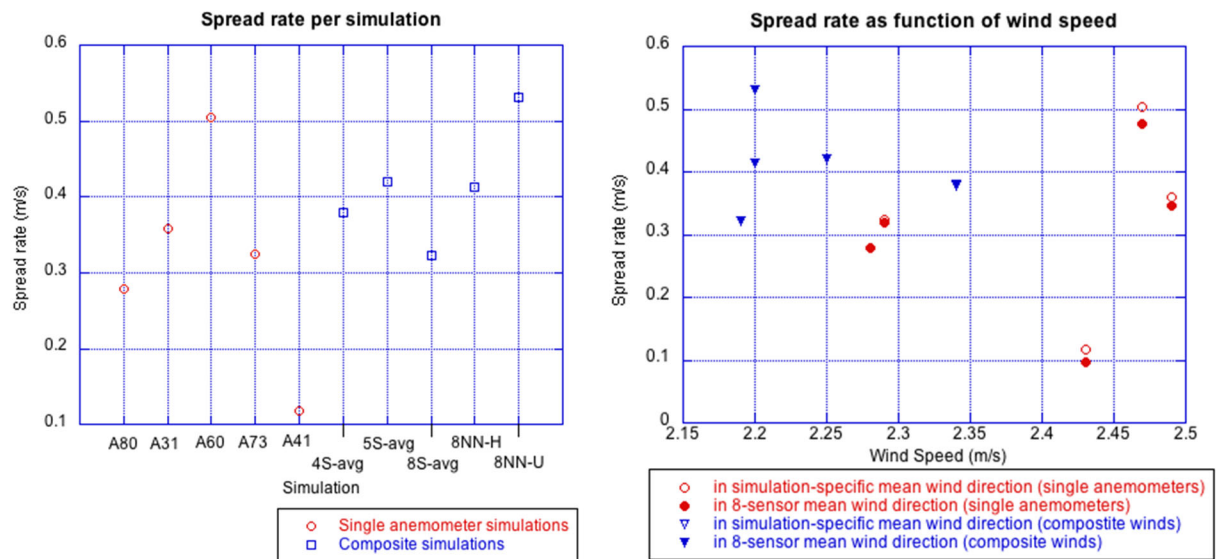


Figure 22a and 22b. Spread rates plotted as a function of simulation specific wind speed.

Within the set of composite simulations with heterogeneous fuels the range of spread rates was much narrower than the range for the individual sensors, 0.38 m/s to 0.42 m/s (~9% range). This is related to the fact that there is less variation in mean wind speed, 2.19 m/s to 2.34 m/s (~7%), as well as the tighter range of mean wind directions that only spans about 10 degrees. The narrower range of average wind angles means that the projection of the ignition line that is perpendicular to the wind speed is much more consistent than amongst the single anemometer runs. There is only 2 degrees of difference in the mean wind angle for the three composite simulations that include anemometer A41. Because the wind angle for sensor A41 is

approximately 25 degrees different from the other four anemometers, the fourth composite simulation that did not include sensor A41 was about 8 degrees off of this tight range.

Another way of comparing spread rates is to compute their spread in the direction that could hypothetically be considered the mean wind at the site. For this purpose, the mean wind direction based on the average of all 8 upwind sensors was calculated. The effective spread rates in this direction were estimated by taking the projection of the simulation-specific wind on this 8 sensor-average direction, which was -20.34 degrees. The results of this second rate of spread calculation are shown in Fig.22b above. Using this method of estimating spread in the 8 sensor-average direction, these values are a fraction of the simulation-specific wind speed spread rates. The trends in rate of spread in the direction of the 8 sensor average wind were similar to those in the directions of the simulation-specific mean winds, with the fastest spread rates in the A60 and 5S_avg simulations and the slowest spread rate in the 8-sensor average mean wind speed recorded at sensor A41. This is expected since the 8-sensor average direction spread rate is just the projection of the actual spread rate. The angle between the fastest raw spread rate, sensor A60, and the 8 sensor-average direction was only 19 degrees. There is only 1 degree difference with 5S-avg. On the other hand, the A41 simulation had a 36 degree difference, and so the projection was a smaller proportion of the raw rate of spread. All of the composite simulations were fairly well aligned with the 8-sensor average wind and thus their projected rates of spread were fairly close to the raw rate of spread values in the direction of the simulation specific winds.

The area burned at 320 seconds also shows considerable variation amongst the simulations performed with winds from single anemometers, ranging from 1212 m² to 5424 m². Like the ROS values, these values are impacted by the direction of the mean wind speed compared with the ignition line. When the winds are more parallel to the fire line the perpendicular width of the fire is reduced, resulting in the area burned being less. The composite winds produced much more consistent areas burned when the heterogeneous fuels were used, ranging from 3444 m² to 4404 m².

The simulation with the homogeneous fuels, 8NN-U, can be compared to the 8NN-H since they have the same wind conditions. There is a significant difference in spread rate (29% difference) and area burned (60% difference). The rate of spread and area burned are larger in the simulation with the homogenized fuels, indicating that locations where the fuels challenge fire spread have a larger impact than those where fire spreads easier than the mean fuel load. This highlights the nonlinear influence that fuels have on fire spread. The fact that the percentage difference for area burned is so much larger than the percentage difference for spread rate indicates the fuel heterogeneity influences both the forward spread and lateral (or flanking) spread of the fire.

Figure 20 illustrates that amongst the single anemometer simulations, the simulated fires with the most burn area are those with winds most perpendicular to the ignition line. However, these are also the simulations with the largest mean wind speeds. An exception is the A41 simulation mean wind speed, which is greater than A73 or A80 and yet the burned area is significantly lower.

Most importantly, Fig. 20 and 22 illustrates the range of simulated fire behaviors that result from using 5 different measured wind speeds that were all observed within 120 m of the fire line. Even though the mean wind speeds are within 15% of each other, the differences in details (wind fluctuations and orientation of the winds with respect to the ignition line) of the winds measured at these 5 locations drive a wide range of fire behaviors. A73 and A80 simulations showed similarities to observed fire spread patterns. However, the clear challenge would have been to know which anemometer to use *a priori*. If you were only placing one anemometer, the question is where to place it. Neither A73 nor A80 were placed directly upwind of the middle of the ignition line, especially if you use the wind direction observed at the anemometers themselves.

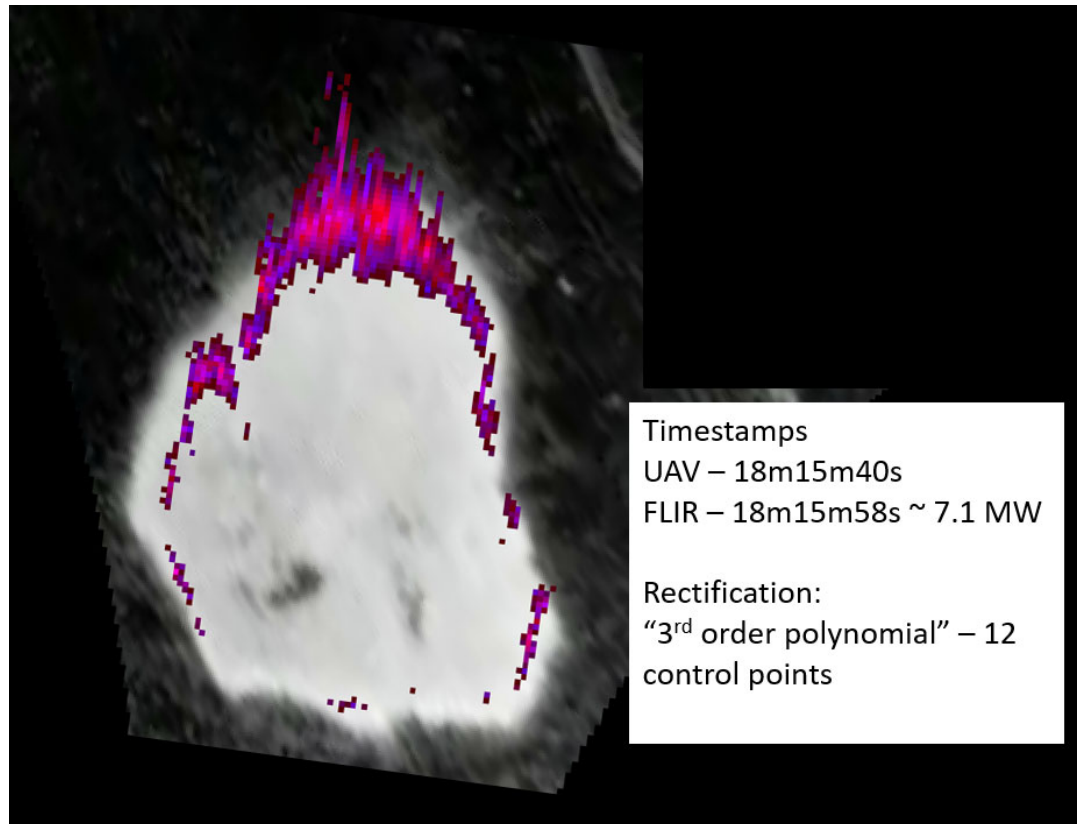


Figure 23. Combined images of S5 burn from overhead drone and boom-mounted FLIR, approximately 320 seconds from beginning of ignition. Image courtesy of Joe O’Brien and Tom Zajikowski (USFS).

Figure 21 illustrates that although the details of the simulated fires in the composite wind simulations are different, their spread rate, area burned, and general spread patterns are much more similar than the range of simulated fires from single anemometers. This should not be unexpected given the greater similarity in wind speeds and directions. Through comparison with observed fire perimeters at 320 seconds illustrated in Figure 23, the simulated fires in the composite wind simulations have spread patterns that have significant similarities to the observed fire spread patterns. Based on this comparison, developing wind fields from combinations of measurements provide some benefits over the use of a single anemometer. The importance of localized variations that are observed at individual anemometers are moderated by

combining them with variations from other locations. The variation in wind direction illustrates that caution should be used in associating any single measurement with the spread of the fire. Figures 24 and 25 highlight similarities and differences between the S5 burn and 8 sensor nearest neighbor algorithm simulation at 320 seconds.

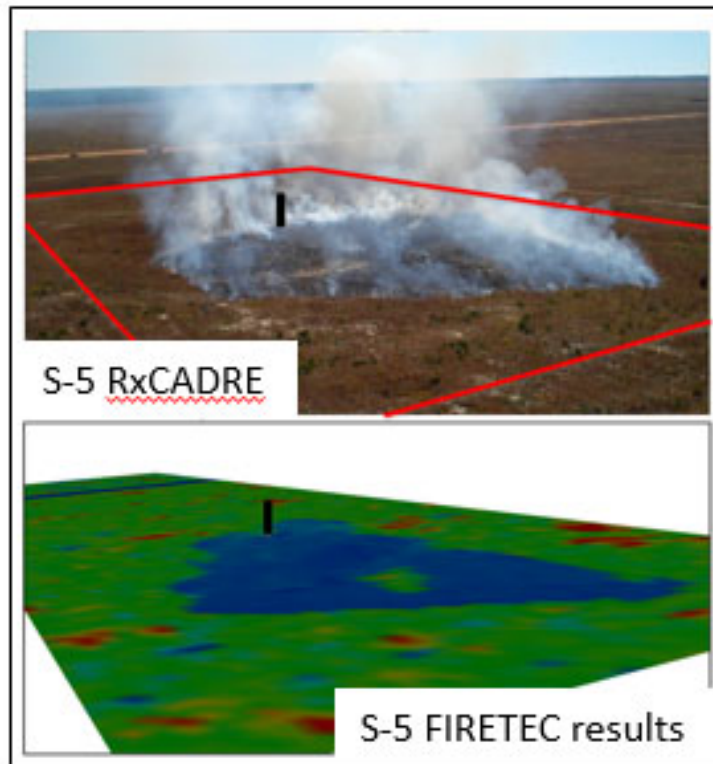


Fig. 24 S5 burn from RxCADRE (top) and FIRETEC simulation, both at 320 seconds after ignition. The red lines in the top image show the extent of the FIRETEC computational grid. The black marker in the center of each image marks the location of an instrument tower. The large blue area in the bottom image 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.

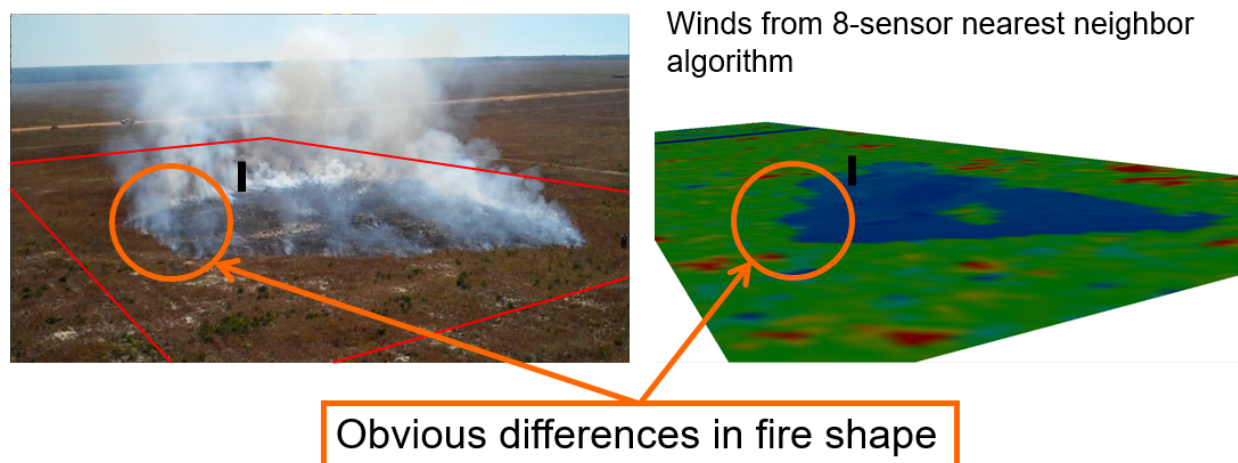


Fig. 25 Shape comparison between S5 burn and FIRETEC simulation at 320 seconds using nearest neighbor algorithm for averaging anemometer windspeeds. Vertical black mark denotes tower location.

6.1.2 Radiative fluxes

Another metric for comparison between fire simulations and observations is the radiative flux. The challenge in performing this type of comparison is that flux was measured at a single specific location in the S5 experiment. Because the fire's behavior is heterogeneous, observations at various points will be different (have a range of values) depending on the correlations between very local winds and details of the fuels, this range was not explicitly measured via a single observation. The second complication is that the specific locations of the hot updrafts and forward bursts in the simulation should not be expected to be identical to the observations even if we knew the details of the wind conditions, much less the influences of the unknown factors in the winds (described above). For this reason, we compared a range of flux values from different points in the simulation to the observations from one location (often this is done in reverse with a simulation data point being compared with a suite of observations). We chose the fluxes emanating upwards from five locations in the vicinity to the observed vertical heat fluxes, which was at the center of the experimental plot. These 5 locations are shown in Figure 26. The idea behind comparing 5 locations to the single observation is to illustrate the range of heat fluxes from various locations and understand whether the measured heat flux is within this range.

The vertical heat fluxes computed within the simulations were recorded based on the energy passing through a 2 m x 2 m horizontal plane at 3.3 m above the fire because this is the height of the top of the second cell above the ground, whereas the measured heat fluxes were measured 4.5 m (height of the tall infrared tripod measurement system). Because there are no canopy fuels to absorb this radiation that is traveling vertically out of the fire, the most significant effect of this difference in height is that the measured sensor includes vertical flux from a wide geographical area and thus the temporal signal is expected to be more diffuse in time or show less well defined variations. In other words, the strongest flux will be coming from the fire when it is directly below the sensor but the sensor also measures the vertical components of the radiative heat flux from other portions of the fire. The higher the measurement the less concentrated the signal

from the fire directly below the sensor and the larger the contribution from adjacent areas (the sensor sees a larger ground footprint).

The vertical radiative flux is plotted as a function of time for the 5 virtual sensor locations (colors) and for the tall infrared tripod sensor (black) in Figure 27. Figure 27 illustrates that for the time of peak vertical radiative heat flux the observation is within the range of the values from the five virtual sensors. The temporal patterns shown in this figure do illustrate that the measured heat flux has a gentler rise and fall, which we attribute to the difference in height of the measurements vs. the virtual sensors as discussed above.

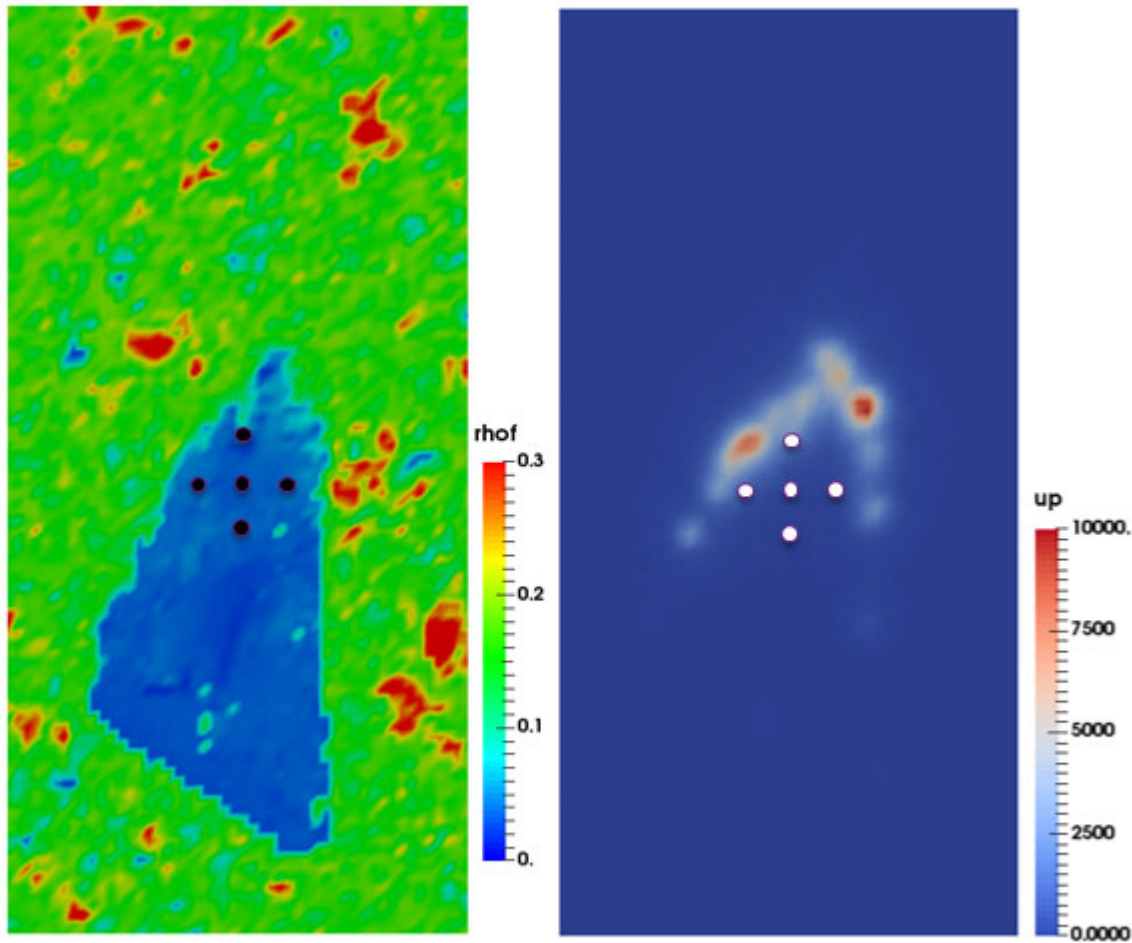


Figure 26. Locations of points used for upward radiation flux comparison in relation to fire perimeter in 8NN simulation (left) and upward vertical radiative flux (W/m^2) map (right). Both of these images are from the 8NN simulation at 320 s after ignition.

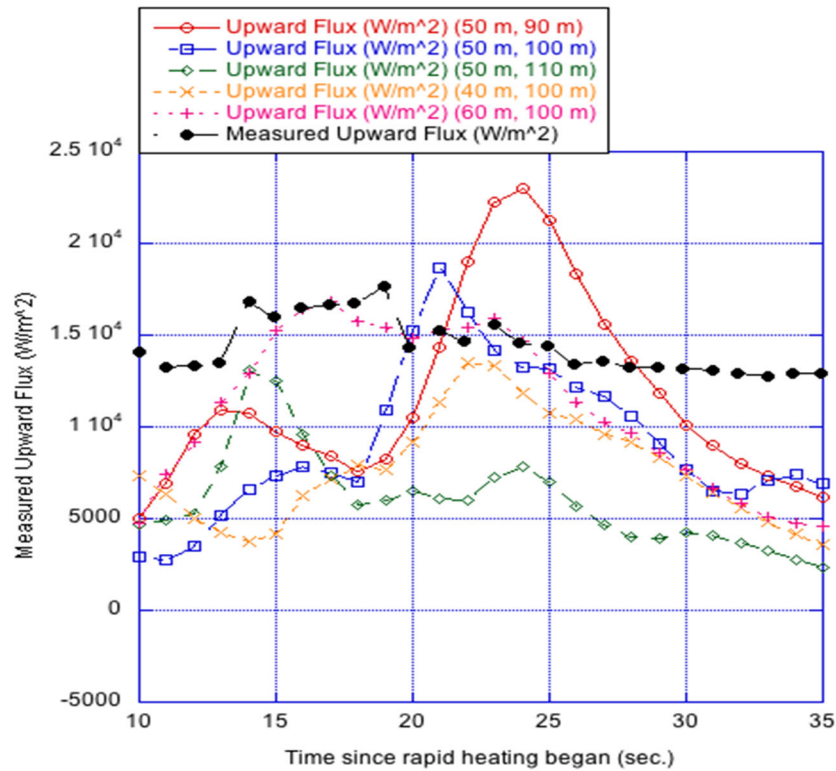


Fig. 27. Measured upward flux as related to time since rapid heating began.

Figure 28 on the following page illustrates the comparison between the peaks of the observed and simulated vertical flux in the form of a box/whisker plot. This graphical description of the distribution of the peaks of the simulated peak fluxes illustrates that observed maximum radiation falls within half of a standard deviation of the mean peak vertical radiative flux (among the 5 locations in the simulation).

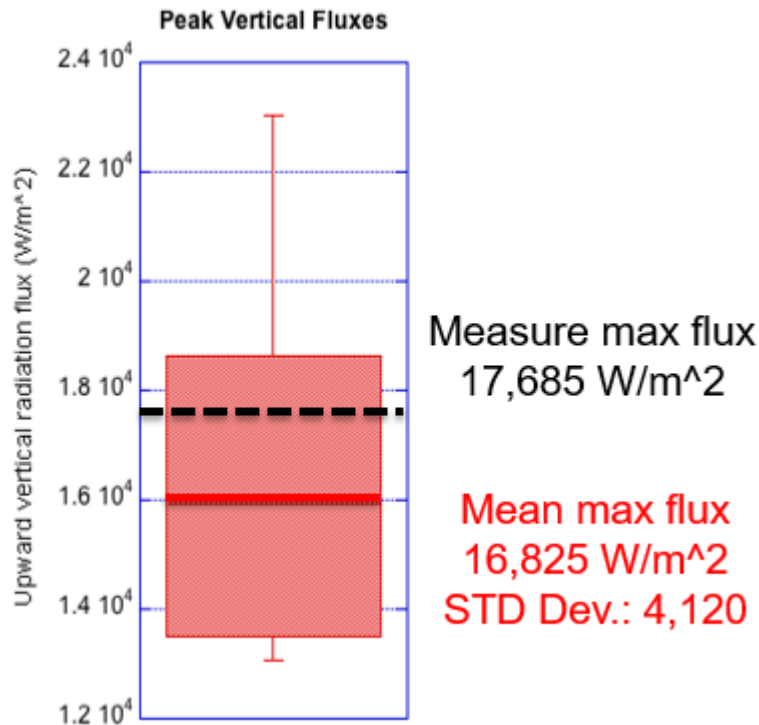


Figure 28. Comparison between simulated and measured peak vertical radiative heat fluxes. The difference between the measured maximum vertical heat flux is within half of one standard deviation of the mean maximum vertical flux (mean among 5 locations).

Direct conclusions –

- FIRETEC spread predictions were appropriate in magnitude
- FIRETEC spread patterns for RxCADRE S5 plot burns were heavily influenced by the details of the prescribed boundary conditions
- 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)
- Models should be used more extensively in the design of future fire experiments in order to improve understanding of the data adequacy

6.2 Performance Objective 2. Simulate prescribed fire behavior and phenomena in longleaf pine fuels on Eglin AFB

FIRETEC performed exceptionally well in meeting the success criteria for the first metric which 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.” Specifically, Ninety-four percent of the 36 workshop attendees “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.”* Response has been similarly enthusiastic from prescribed fire practitioners following presentations at various forums.

The success criteria, “Simulated results capturing known response to changes in ignition configuration including line and spot ignition separation distance under different wind and fuels conditions will be within one standard deviation of rates and directions of spread measured in 2008, 2011 and 2012 RxCADRE campaigns.” was not met due to insufficient data and comparable replication across RxCADRE burn units and years, as well as the inability to replicate the variable firing patterns, fuels and weather associated with the RxCADRE forested burns. Sampling design, response variables, and instrumentation varied considerably across RxCADRE campaigns from year to year and across forested burn units within a year, precluding the ability to calculate means and standard deviation in rates and direction of fire spread due to these inconsistencies and variability in fuels and weather across years and burn units.

In addition to the quantitative analysis described in Section 6.2.2, project FIRETEC simulations were used to visually illustrate and evaluate FIRETEC’s ability to simulate realistic fire phenomenology in Eglin’s longleaf pine forest fuels. Figure 29 illustrates FIRETEC results for solid ignition line (ATV) scenarios from the “Baseline Fire Simulations” diagramed in Figure 7, on page 22. FIRETEC modeled appropriate relative spread rates for varying vegetative structures and wind speeds and for general fire phenomenology associated with multiple ignition lines. Specifically, increased vegetation induced wind drag and associated decreases in rates of spread were captured as canopy (without midstory), and then canopy with midstory were added to the grass (non-forested) fuels. Additionally, FIRETEC captured the increased fuels consumption (loss of fuel mass) in the forest midstory and canopy as illustrated by the dark brown and black “burned” areas, respectively, as additional lines of fire were added. Black areas indicate areas where canopy mass loss (consumption) is greater than 30% within a given FIRETEC voxel.

The concept of increased fire behavior and midstory/canopy consumption in response to an increased number of simultaneous ignition lines is widely understood by prescribed fire practitioners. Therefore, varying the number of simultaneous ignitions lines is a common strategy used to manipulate fire behavior for meeting specific management objectives. Though this causal relationship is common knowledge among experienced prescribed fire managers, FIRETEC’s ability to clearly capture the increased intensity resulting from the interactions between multiple ignition lines is significant.

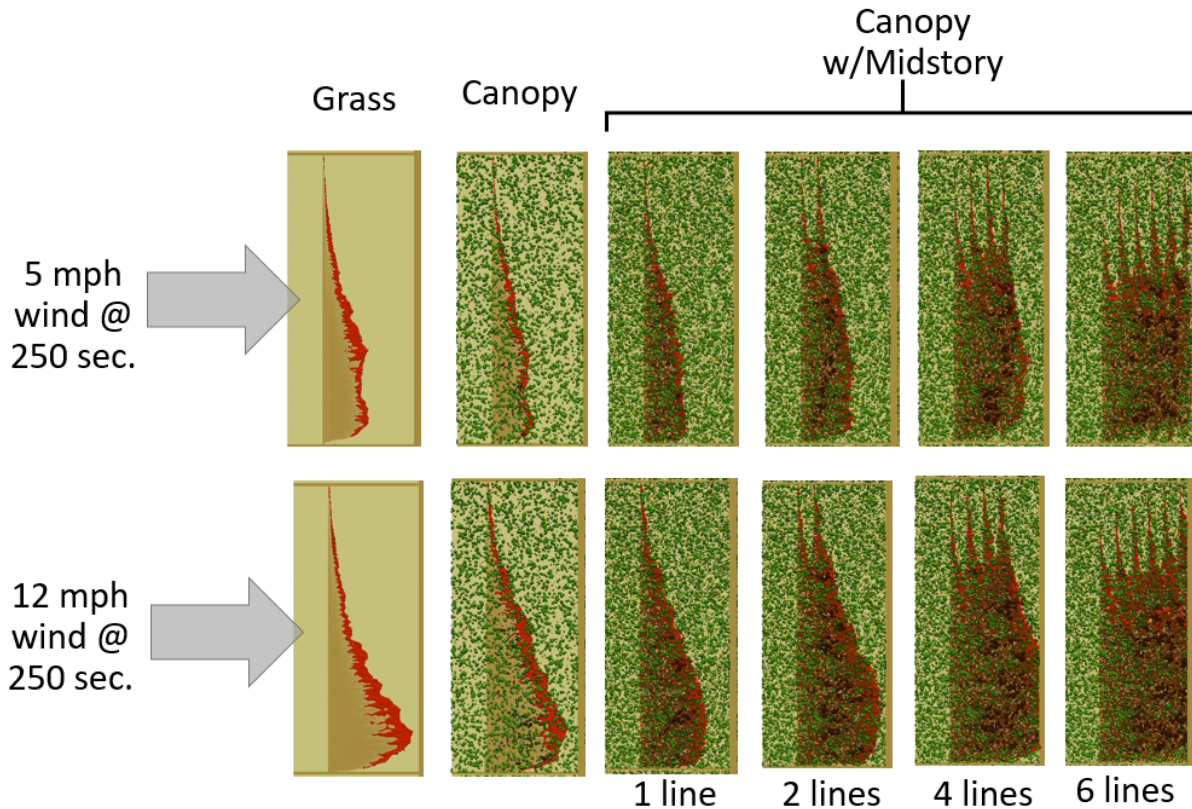


Fig. 29. Baseline fire scenarios modeled with FIRETEC. The images are bounded by the fuel breaks and therefore do not show the entire computation domain.

Ocular comparisons of simulation results from the initial “Fire Phenomenology Study” diagrammed in Figure 8, on page 22, are illustrated below in Figure 30. Again, FIRETEC met fire managers’ expectations by illustrating increased consumption with increased amounts of fire applied per unit area. Point source “aerial” ignition and 6m dash ignition produced lower consumption than 14m dash ignition. “Closing flanks” by lighting them after the interior is ignited with strip head fire produced the most intense fire behavior overall, as expected. Also, as expected, lower wind speed produced lower overall fire intensity than higher winds for each of the simulations illustrated below. The “Open Midstory” scenario, which represented reduced fuel loadings with minimal midstory structure and increased fuel moistures, produced less intense fire behavior than other 5-line strip ignition simulations with “standard” fuel loadings.

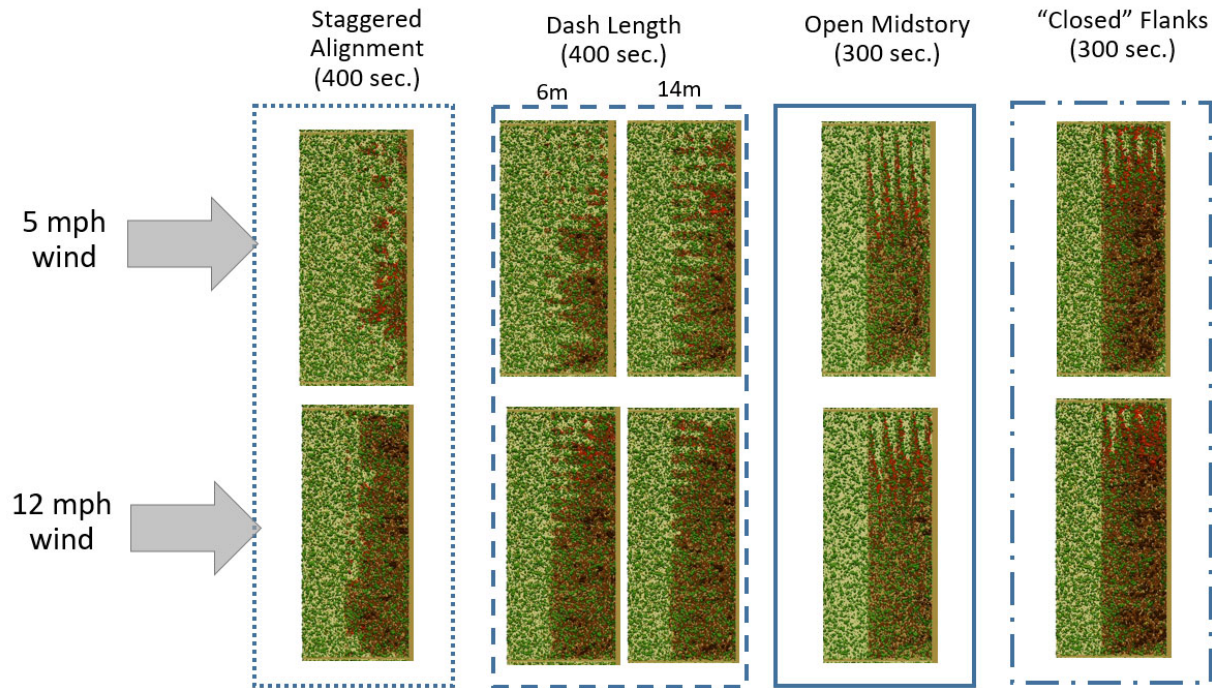


Fig. 30. Five-line ignition Fire Phenomenology Study. As with Figure 29, these images are bounded by the fuel breaks, and so do not show the entire computation domain.

In addition to evaluation of spread rates and fire intensity for different scenarios, general differences in convective lift as an indicator of plume lofting were portrayed and compared. “Plumes” depict gasses ≥ 350 K (170 F), as illustrated in the comparison between five line ATV and aerial point source ignition in Figures 31 and 32. In these simulations, the lines of fire generated by the ATV strip head fire ignition show greater plume height and volume than the aerial point source ignition since the small individual fires resulting from aerial ignition are widely dispersed and burn together slowly compared to the solid lines of fire ignited by the ATVs.

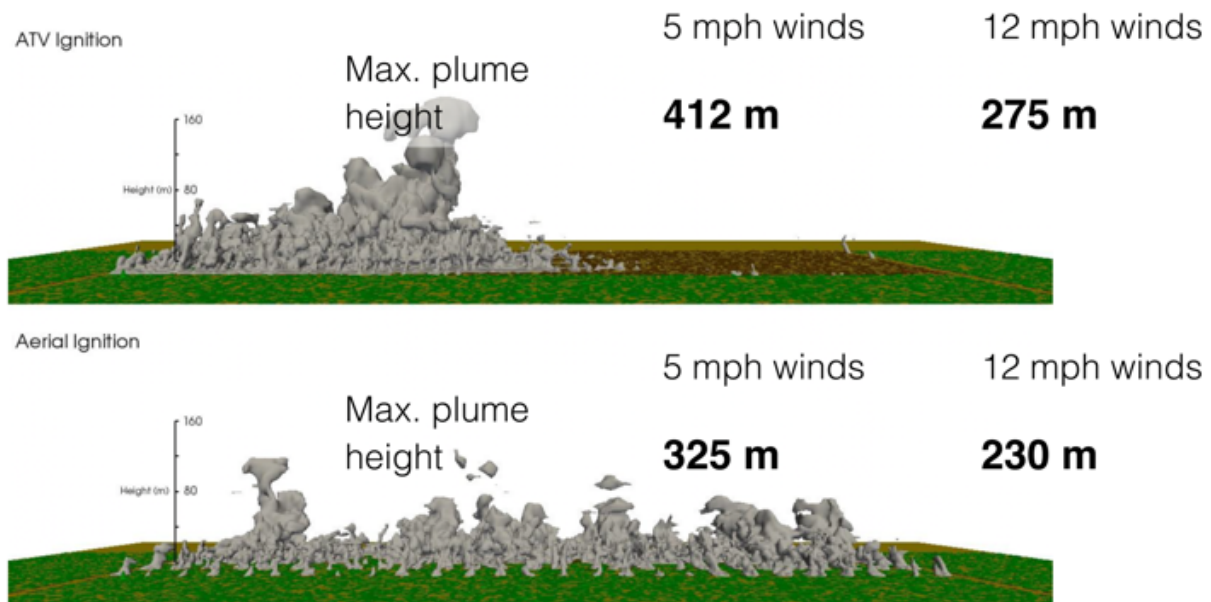


Fig. 31. View from upwind illustrating differences in modeled maximum plume heights between 5-line, 41 acre ATV and aerial point source ignitions.

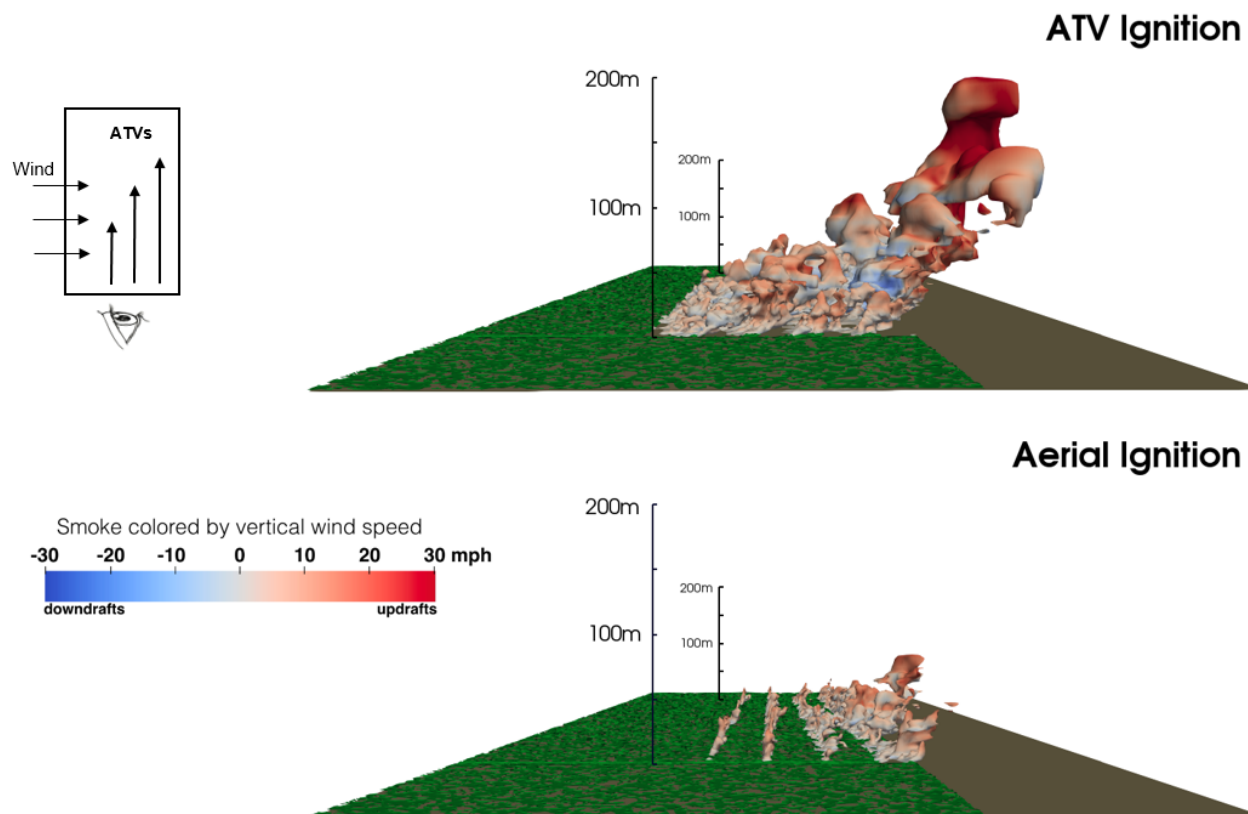


Fig. 32. Crosswind view indicating plume height three minutes after ignition begins with 12 mph wind comparing ATV strip head fire ignition with aerial point source ignition. “Trees”

were removed for visual clarity. Plume color denotes vertical wind speed of heated gasses.

6.2.1 FIRETEC sensitivity to variations in fuel bulk density/loading and live fuel moisture:

Although the fuel beds are based on field data, there is variability in the productivity, composition, and arrangement of fuels across various sites even across Eglin. In order to assess the sensitivity of simulations to this sort of variability, variations in fuel bulk density for canopy and midstory fuels were used in simulations to test the sensitivity of FIRETEC to variable fuel bulk densities. For these tests fuel bulk density was increased by 30% for both the “midstory/low fuel moisture” and “open midstory/high fuel moisture” cases. Appendix B includes detailed information regarding the fuel loading and fuel moisture for these simulations. The paired images in Figures 33 through 38 provide comparisons of FIRETEC results for the differing fuel bulk densities, firing patterns and fuel conditions. Lower bulk density simulations are on the left in each figure. Varying modeled intensities are indicated based on the amount of canopy fuel consumed (blackened area representing >30% simulated canopy consumption). All of these paired images represent FIRETEC model runs with 5 ignition lines, 500 seconds after ignition begins with winds blowing from left to right. Figures 33, 35 and 37 represent simulations with the “midstory/low fuel moisture” fuels conditions used in the majority of simulations in this project, while 34, 36 and 38 represent “open midstory/high fuel moisture” fuel.

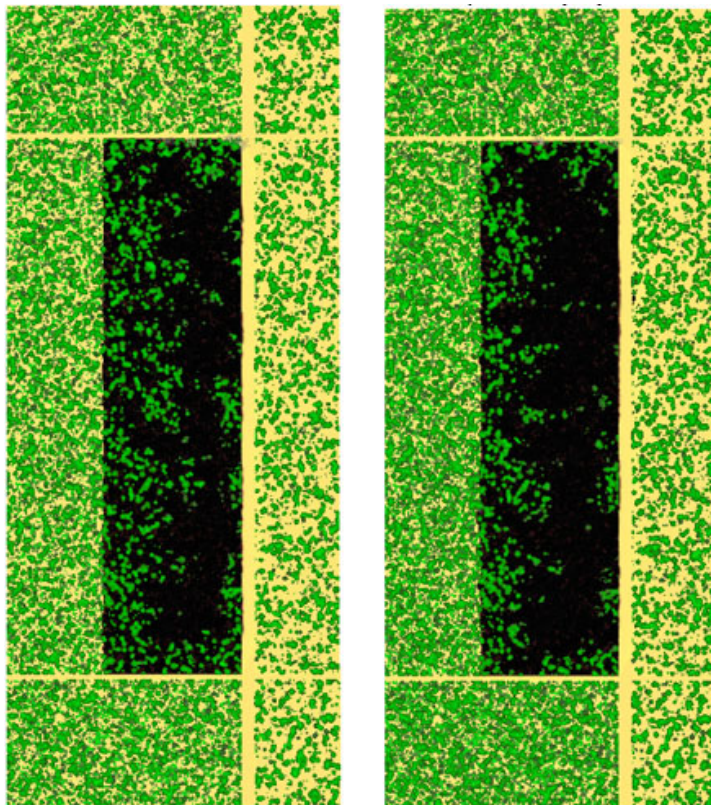


Fig. 33. Environmental and ignition factors in these FIRETEC simulations (12 mph wind, “midstory/low fuel moisture” fuels, 5 line ATV ignition) represent conditions expected to produce relatively intense fire behavior due to wind driven head fire. More canopy consumption is clearly indicated with the higher fuel loadings on the right. As expected, overall canopy consumption for both scenarios is higher than for corresponding fuel loadings in Figures 35 and 37.

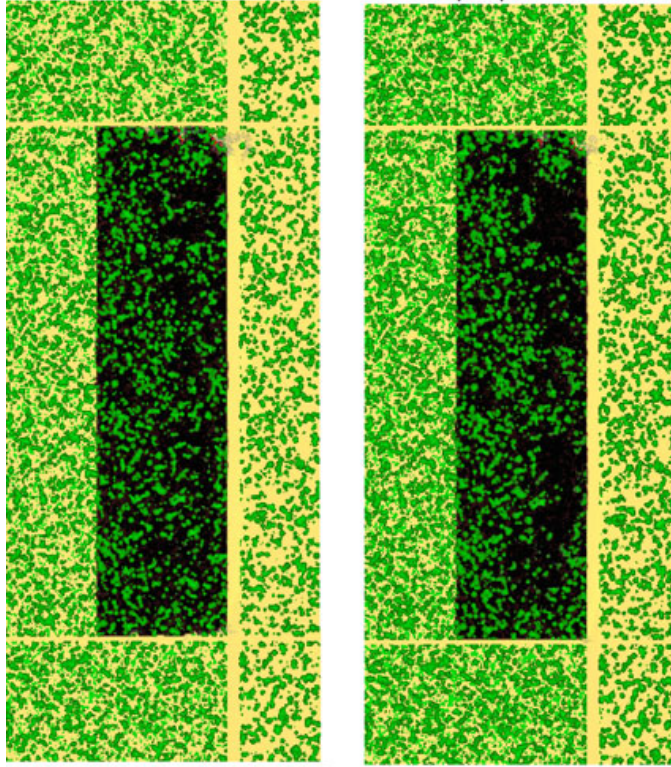


Fig. 34. This set of images depicts FIRETEC simulations with 12mph winds, “open midstory/high fuel moisture” fuels (as described above), and 5 line ATV ignition. This is a much milder burning condition than is shown in Figure 33. Thus, as expected, modeled fire intensity is lower than in Figure 33. Once again, higher fire intensity is indicated in the simulation shown on the right due to higher bulk density (heavier fuel loading).

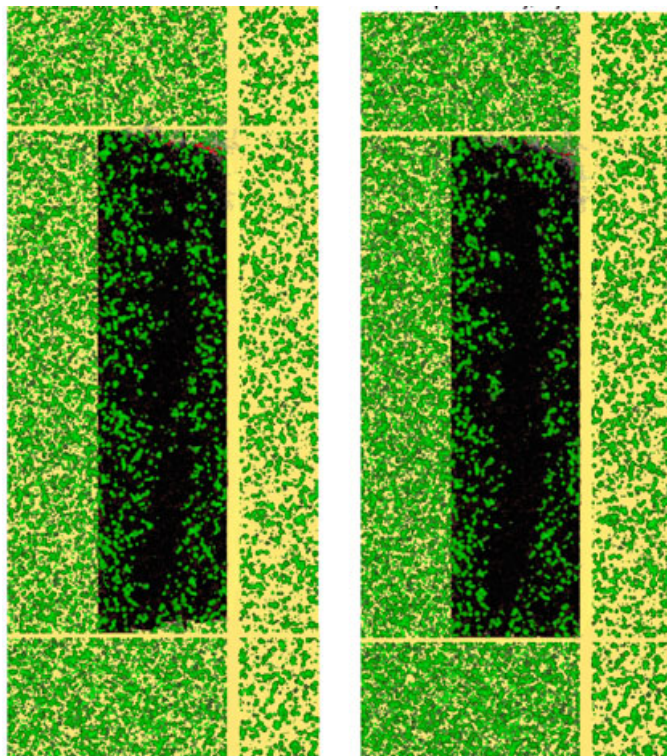


Fig. 35. In this paired set, simulating 5mph winds with “midstory/low fuel moisture” fuels and 5 line ATV ignition, the right image once again shows greater intensity due to higher fuel loading, but with a significantly different scorch pattern than that seen in Figure 33. Under this light wind scenario, FIRETEC modeled the ignition lines pulling together due to convective lift, producing a clearly visible line of canopy consumption on the interior of the block. This phenomenon of fire “drawing to the middle” is commonly observed on prescribed fires when setting multiple lines of fire under light wind conditions. In this comparison, consumption increased from 32% to 45% with the increased fuel bulk density.

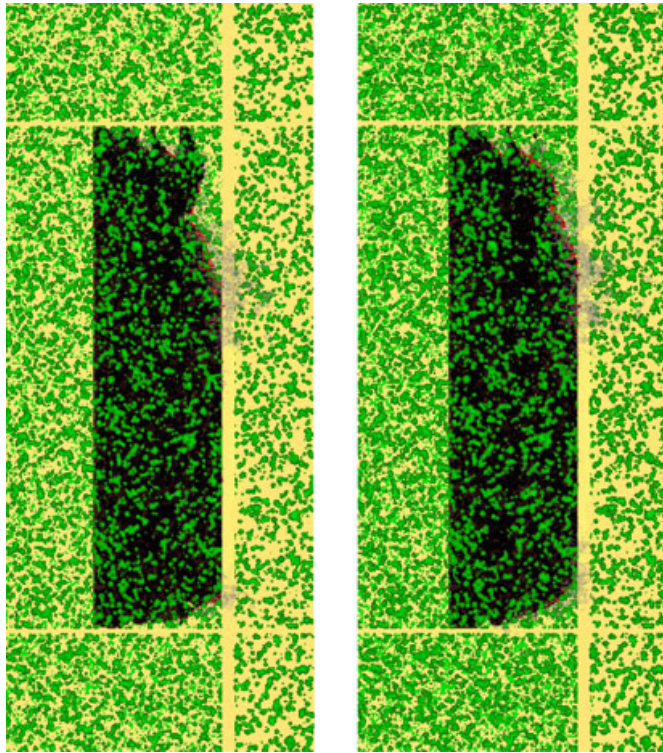


Fig. 36. Under the mild burning conditions in this scenario (5 mph winds, “open midstory/high fuel moisture” fuels, and 5 line ATV ignition), modeled fire intensity is low and fire spread is the slowest of the strip head fire ignition scenarios as evidenced by the area not being completely burned out. It is also noteworthy that the lower right corners have not burned out, despite being the first area ignited.

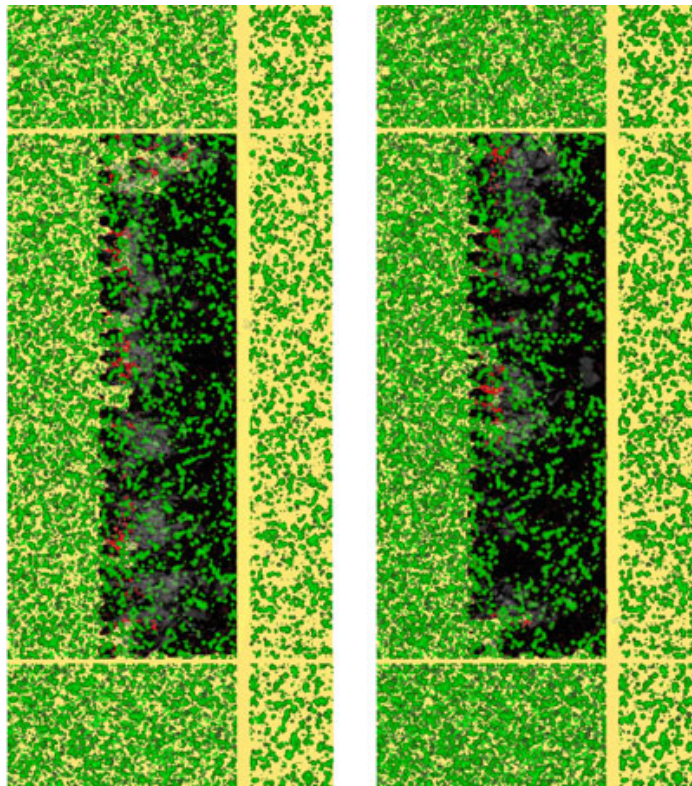


Fig. 37. Compared to Figure 33, which uses the same 12 mph wind and “midstory/low fuel moisture” fuels, this aerial point source ignition shows much lower overall intensity. This is typical of differences in intensity between strip head fire and point source ignitions.

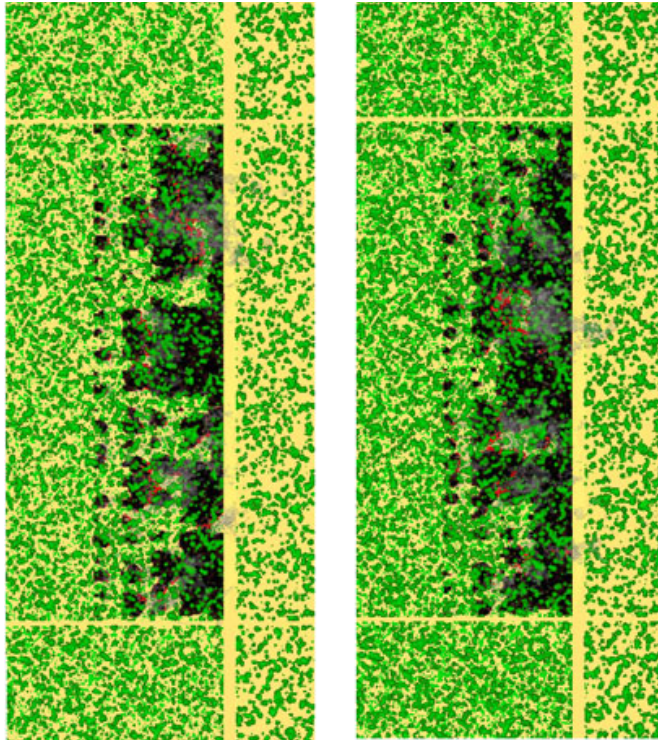


Fig. 38. This paired set represents mild overall burning conditions with point source ignition, 12 mph winds, and “open midstory/high fuel moisture.” Under these more marginal burning conditions, even with 12 mph wind, differences in intensity between the paired set is not as discernable as in the previous figures. Note that point source ignitions are much slower to burn out the area than the strip head fire under identical fuel and wind conditions represented in Figure 34.

6.2.2 Sensitivity of FIRETEC to changes in firing patterns and environmental factors as illustrated by % consumption

For this project, where the focus was on comparing general phenomenology associated with various environmental factors and ignition scenarios, comparing modeled differences in fire behavior was possible via comparisons of stand-scale fuel consumption between the various simulations. The comparison of modeled consumption provided valuable insights into model performance as well as general differences in modeled intensity between the different ignition methods and environmental conditions. Fuel consumption was calculated for three different strata in the forest fuel bed, understory, midstory and canopy, as well as for different fuel moisture and fuel loadings. Appendix B describes these fuel strata and conditions. Appendix C includes FIRETEC-generated consumption figures for the baseline scenarios depicted in Figure 7 and the phenomenology study scenarios depicted in Figure 8.

Combined consumption of the midstory/canopy for the “canopy with midstory” baseline scenarios are compared in Figure 39. In this figure, all “aerial” scenarios represent point source ignition and all “ATV” scenarios represent strip head fire ignition. FIRETEC generally met managers’ expectations for capturing phenomenology associated with these different firing patterns and winds. Specifically:

- Higher winds produced greater consumption for all ignition scenarios
- Aerial ignition produced lower overall consumption than ground/ATV ignition
- Higher numbers of ground (ATV) ignition strips generally produced higher consumption

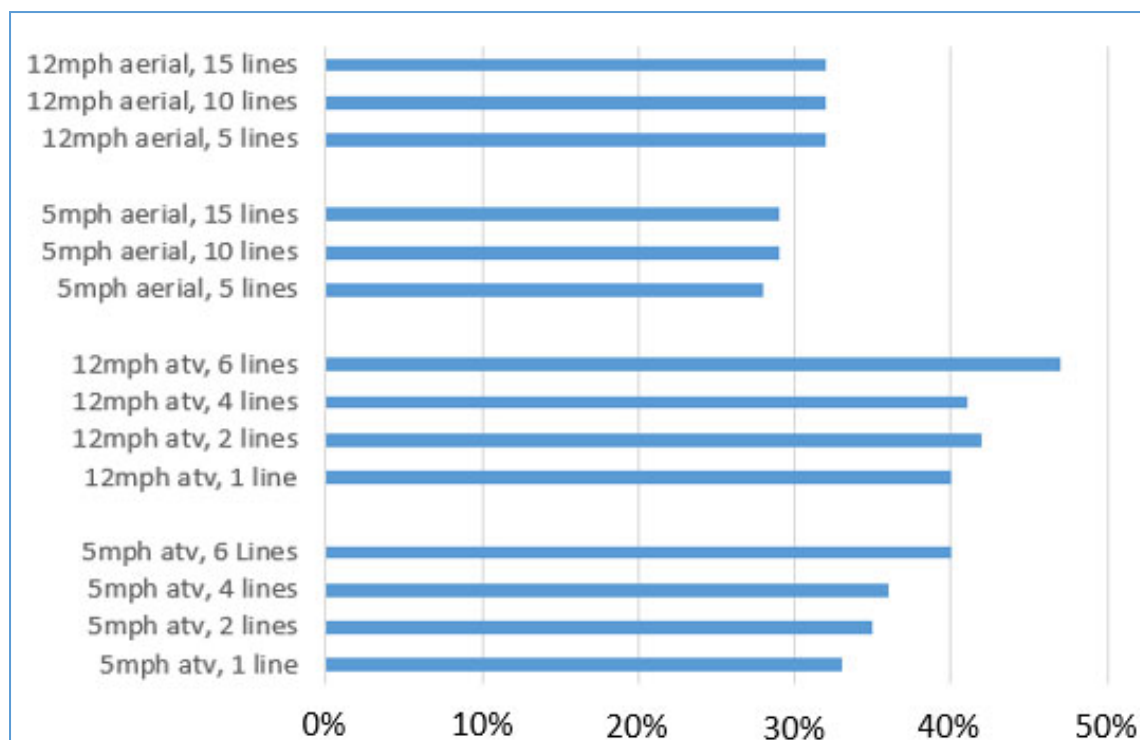


Fig. 39. Comparison of % consumption for combined canopy/midstory for 14 baseline scenarios described in Figure 7.

Consumption comparisons were made to assess FIRETEC’s ability to capture the mitigating effect of an open canopy with lighter midstory fuels and higher fuel moisture using identical 5-line strip ignitions. As illustrated in Figure 40, differences are clearly illustrated with significantly less consumption occurring in the lighter midstory fuel loading/higher fuel moisture scenarios. FIRETEC also met expectations by modeling higher midstory and canopy consumption for the higher winds, particularly for the standard “dry” canopy w/midstory used for most of the simulations. Open canopy with high fuel moisture, labeled “wet” conditions, limited overall consumption in the FIRETEC simulation with little difference in consumption between 5 mph and 12 mph wind speeds. This correlates with fire managers’ typical allowance for a broader range of prescription parameters for these open, fire maintained stands which can be burned under “hotter” and drier weather conditions without causing excessive canopy damage.

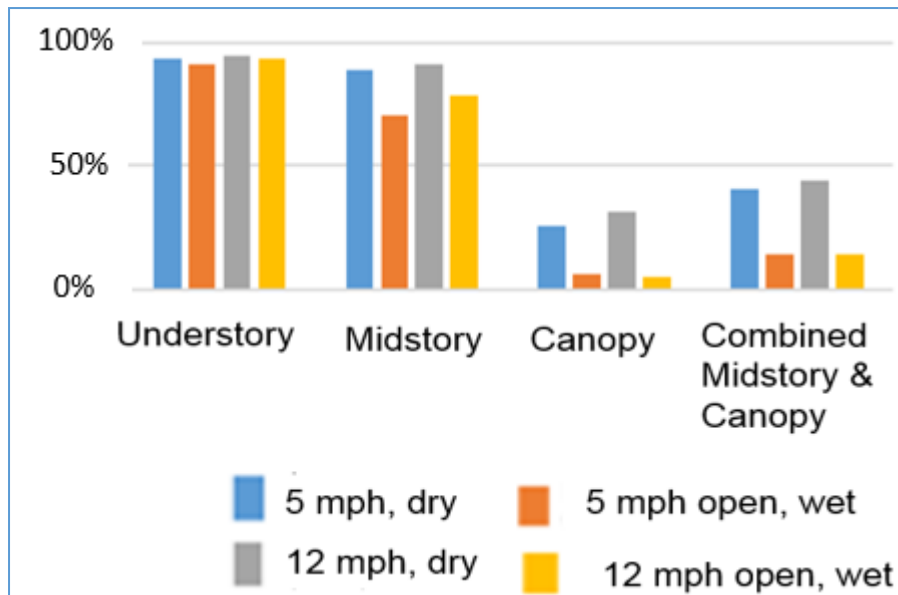


Fig. 40. Consumption comparisons between 5-line strip head fire ignitions with open midstory/high fuel moisture (wet) and standard/dry fuel conditions.

Differences in canopy consumption for various 5-line ignition tactics are illustrated in Figure 41. As expected, “closing the flanks” of the strip head fire simulation with ignition lines generated the highest overall canopy consumption compared to less aggressive aerial point source or 14m dash firing techniques, for both the 5 mph and 12 mph windspeeds.

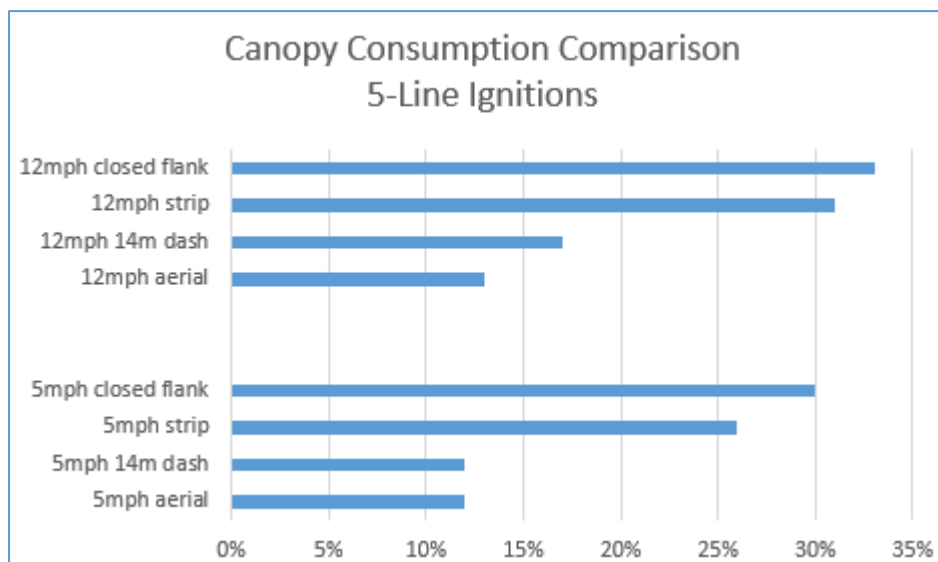


Fig. 41. Canopy consumption comparison for different 5-line firing techniques under 5 mph and 12 mph winds with identical fuels.

In Figure 42 the small horizontal bars represent the mean consumption by "main effect" treatment combinations (windspeed, number of lines, and ignition type) for the combined mass of both midstory and overstory. The stars for each treatment on the X-axis table show that wind speed and ignition type are more significant than number of lines, but number of lines too is statistically significant at $\alpha < 0.05$. With canopy and midstory combined there are no treatment interactions, meaning that increasing intensity is a linear function of these treatment variables. Note that the total consumption is in the 30-40% range with combined midstory and overstory biomass, reflecting the surface fire dominated behavior of this ecosystem.

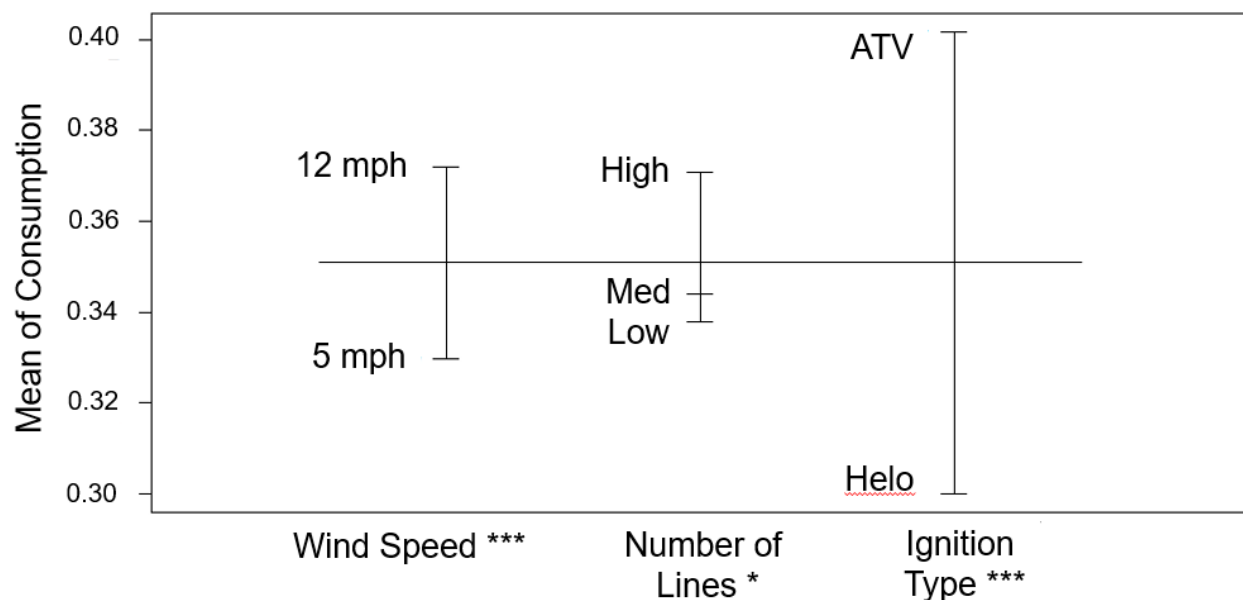


Fig. 42. Spatial statistical analysis of combined canopy and midstory consumption (%) for wind speed, number of ignition lines and ignition type using 3-Way ANOVA. * = $P < .05$, *** = $P < .001$. ATV ignition is strip head fire and "Helo" ignition is point source.

Figure 43 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 (5 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 5 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 force driving consumption results in this analysis which included both canopy and midstory vegetation.

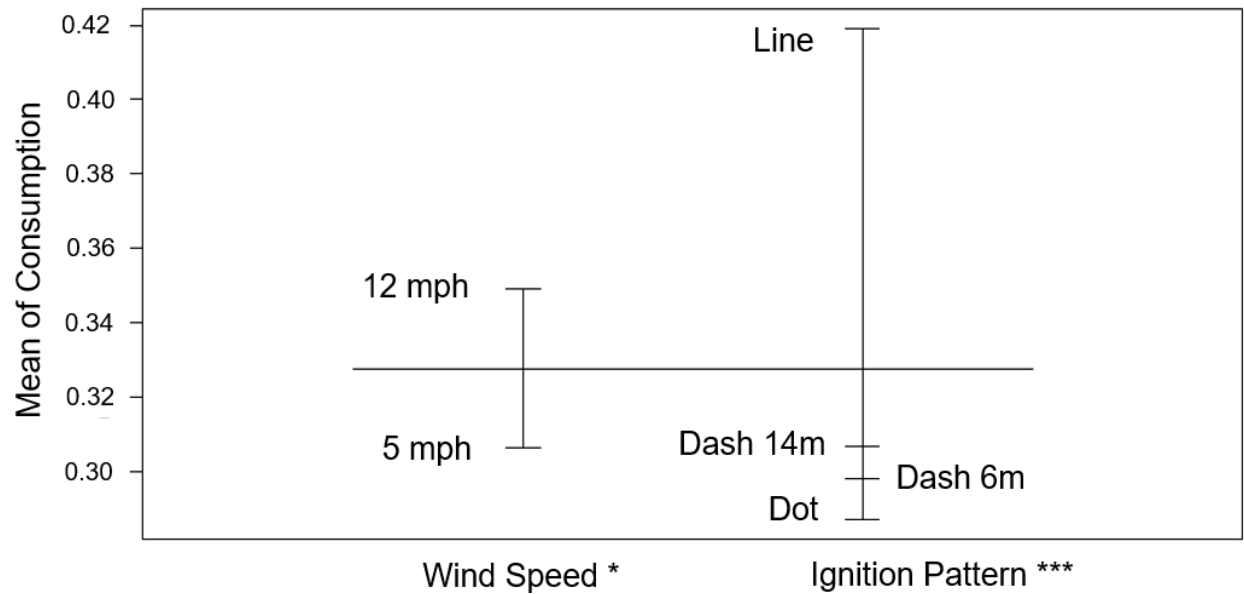


Fig. 43. Statistical analysis of combined canopy and midstory consumption as related to wind speed and ignition pattern. * = $P < .05$, *** = $P < .001$

Figure 44 shows a comparison of consumption in the midstory only. There is not a significant difference in consumption between fast or slow wind for ATV ignitions, but slow winds significantly decrease midstory consumption across aerial point source ignition simulations. The letters show statistically different means, and only slower wind (5mph) aerial point source ignitions show a decreased consumption relative to the other three treatment combinations. While statistically significant, all mean consumption values are in excess of 84%, again illustrating the thorough nature of surface fire consumption in the midstory under these prescribed conditions.

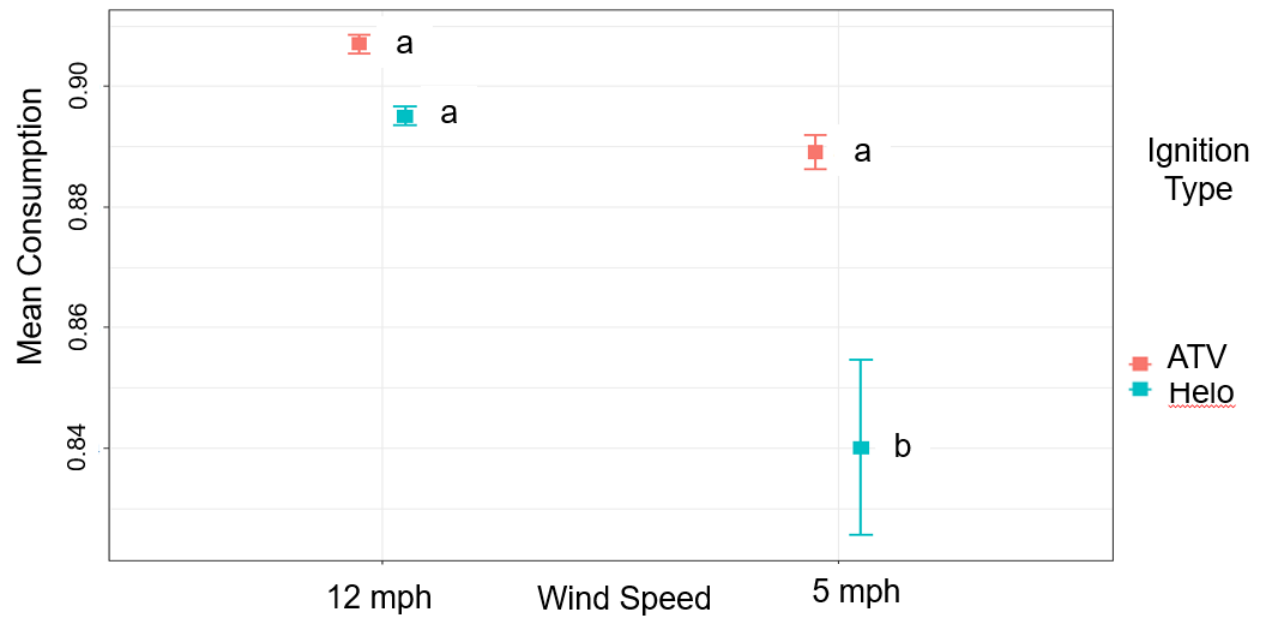


Fig. 44. Statistical analysis of midstory consumption as related to wind speed and ignition type interaction.

Comparisons of FIRETEC-generated rates of consumption for five-line ATV strip ignition and aerial point source ignition at 5 mph and 12 mph winds are illustrated in Figure 45. 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 wind scenarios. Burnout times are noticeably faster with strip ignition when compared to aerial ignition as well. For aerial ignition, wind speed impacts timing of consumption without a significant difference in peak rate of consumption.

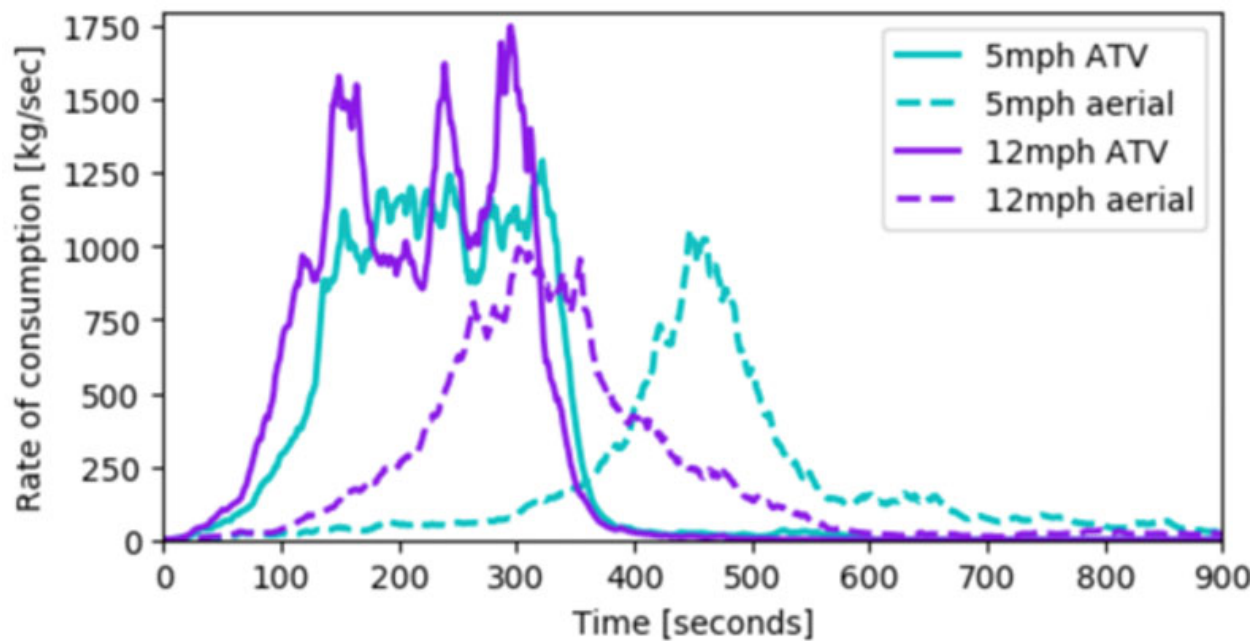


Fig. 45. Timing and amount of fuel consumption for ATV/strip head fire and aerial point source ignition. strategies.

6.3 Performance Objective 3. Use modeling results to enhance knowledge, skills and abilities of fire practitioners nationally.

This project has exceeded expectations regarding outreach and utility to prescribed fire practitioners as project simulations are now included in the curriculum for the National Interagency Prescribed Fire Training Center (PFTC), the premier prescribed fire practitioner training venue in the country. <https://www.fws.gov/fire/pftc/>. This accomplishment could be the single most important outcome of this project for the prescribed fire practitioner community. PFTC uses a combination of classroom and field experience to train approximately 100 individuals per year from State and Federal agencies from across the country.

Other project outreach efforts include:

- Three facilitated workshops conducted at Eglin AFB, Ft. Stewart and Tall Timbers Research Station, which was recorded, <https://youtu.be/3E9KxcoVdP8>,
- Webinar hosted by Southern Fire Exchange: <https://youtu.be/TOrkny2ILik>
- FIRETEC animations available on YouTube: <https://youtu.be/wRebif0tULk>
- Three-part series of articles written by Principal Investigator in Fire Management Today:
 - Article 1: https://www.fs.fed.us/sites/default/files/fire-management-today/fs_firemanagement763_508_v3.pdf
 - Article 2: https://www.fs.fed.us/sites/default/files/fire-management-today/fs_fire_management_v76-4_508_v2.pdf
 - Article 3: Pending at time of writing.

- Articles:
 - “Fire Management Today” Three part series of articles, first two published, third in progress
 - U.S. Forest Service’s “The Chief’s Desk: People, Places and Things”
 - DOD’s “Natural Selections”
 - “Drip Torch Digest”, an online publication by Southeastern Regional Partnership for Planning and Sustainability (SERPPAS)
 - Wired online magazine: <https://www.wired.com/story/how-supercomputers-can-help-fix-our-wildfire-problem/>
- Adobe Connect or Zoom presentations:
 - U.S. Forest Service Washington Office Fire and Aviation Management, Landscapes and Partnerships Staff (Recorded)
 - U.S. Forest Service Washington Office Assistant Director, Capabilities, Development and Integration (Technology Transfer Office)
 - Army Installation Management Command (IMCOM) Wildland Fire Working Group
- Presentations:
 - Association of Fire Ecology Fire Congress Special Session: <https://fireecology.org/2017-Videos>
 - Society of American Foresters Annual Convention
 - Prescribed Fire Science Consortium, Tall Timbers Research Station
 - Air Force Wildland Fire Center leadership
 - Canadian Forest Service
 - North Florida Prescribed Fire Council
 - Poster presentations at SERDP/ESTCP Annual Symposiums and American Geophysical Union
 - Army Reserve Resilience and Sustainability Training
 - International Association of Wildland Fire, 6th Fire Behavior and Fuels Conference
- In addition to PFTC, project FIRETEC simulations are now included in:
 - Fire Effects course, Rx-310 (in Southeast)
 - Florida Department of Environmental Protection’s prescribed fire training curriculum

Products generated from this project have been enthusiastically received by prescribed fire practitioners. Demonstration results are posted on the Fire Research and Management Exchange System (FRAMES) website. The National Wildfire Coordinating Group has been contacted regarding integration of project results into the Interagency Aerial Ignition Guide, but there has been no response as of this writing. As DOD fire managers continue to visit Eglin AFB for hands-on fire training, they will receive direct classroom training on the influence of ignition patterns, forest structure, and environmental conditions on fine and large scale fire behavior and potential fire effects as portrayed by FIRETEC simulations from this project.

The enthusiastic reception of FIRETEC simulations by fire practitioners is due in large part to the number of different ways that data can be visualized to illustrate different fire behavior concepts for training purposes. For example, Figures 48 and 49 below illustrate three different

types of visualizations of the same five-line ATV ignition scenario with 5 mph winds, 180 seconds after ignition begins. Updrafts, indrafts and a “convective core”, common phenomena for this type of ignition scenario, are clearly depicted. In addition to the consumption analysis provided by FIRETEC described in Section 6.2, the short “movie clips” generated for the project, including the visualizations below provide powerful on-of-a-kind visual training tools. Unlike video of an actual fire, FIRETEC can portray fire behavior without smoke as shown on the left side of Figure 46, providing a much clearer view of interactions between flaming fronts and resulting phenomenology. Pairing the FIRETEC movie clips of the “fire” on the left with the wind vectors on the right provides perhaps the most powerful visual training tool for understanding prescribed fire dynamics that has ever been produced for wildland fire training purposes. In the facilitated workshops, this particular set of visualizations, and those depicted in Figures 31 and 32, were consistently ranked as being of very high value for training purposes. Figure 47 depicts convective dynamics through a vertical slice for the same ignition scenario from downwind. Plume dynamics including the well-defined convection column are clearly illustrated.

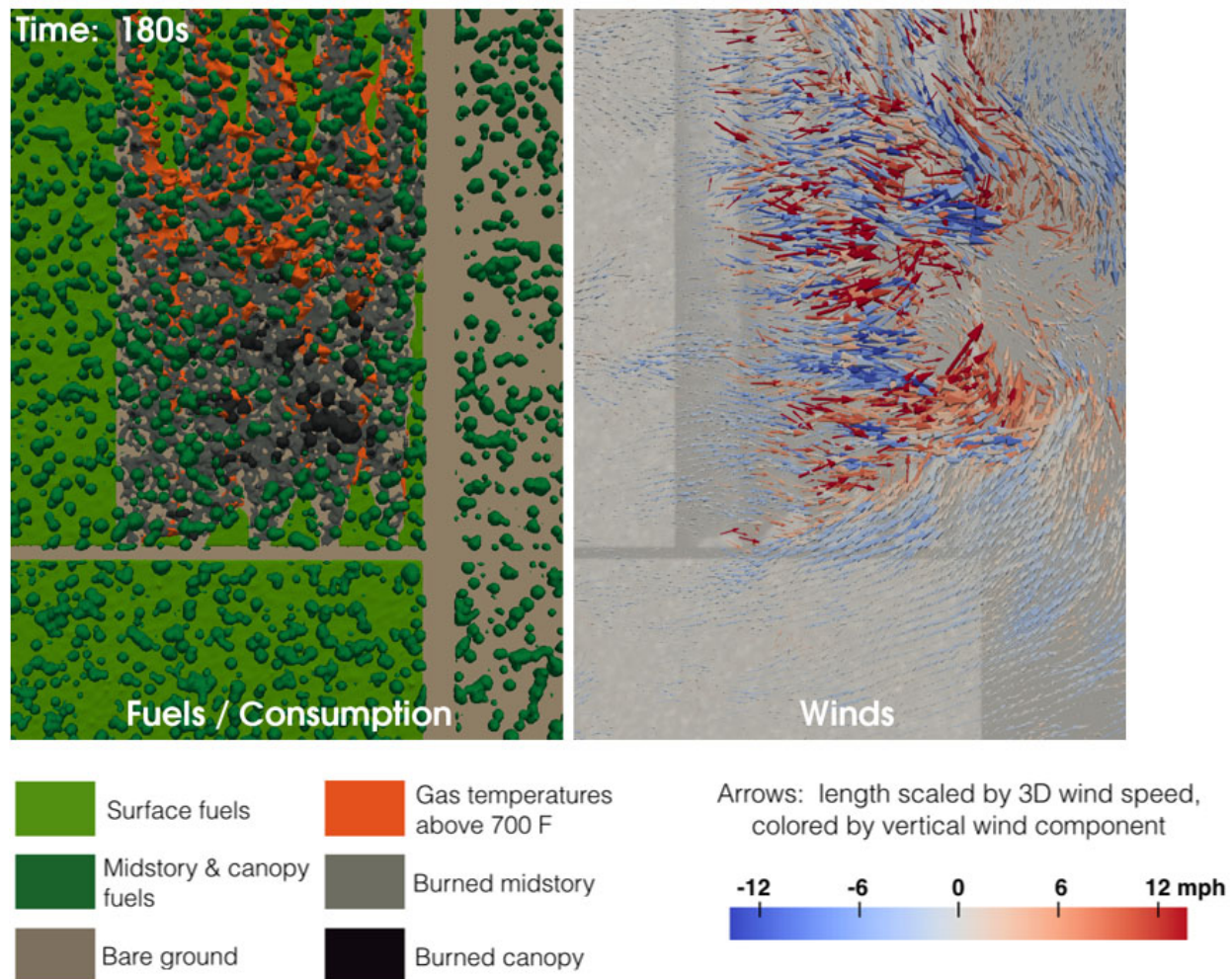


Fig. 46. 5-line ATV ignition with 5 mph winds displayed in “forest fire” context with “smoke” removed on left and as vertical wind vectors on right.

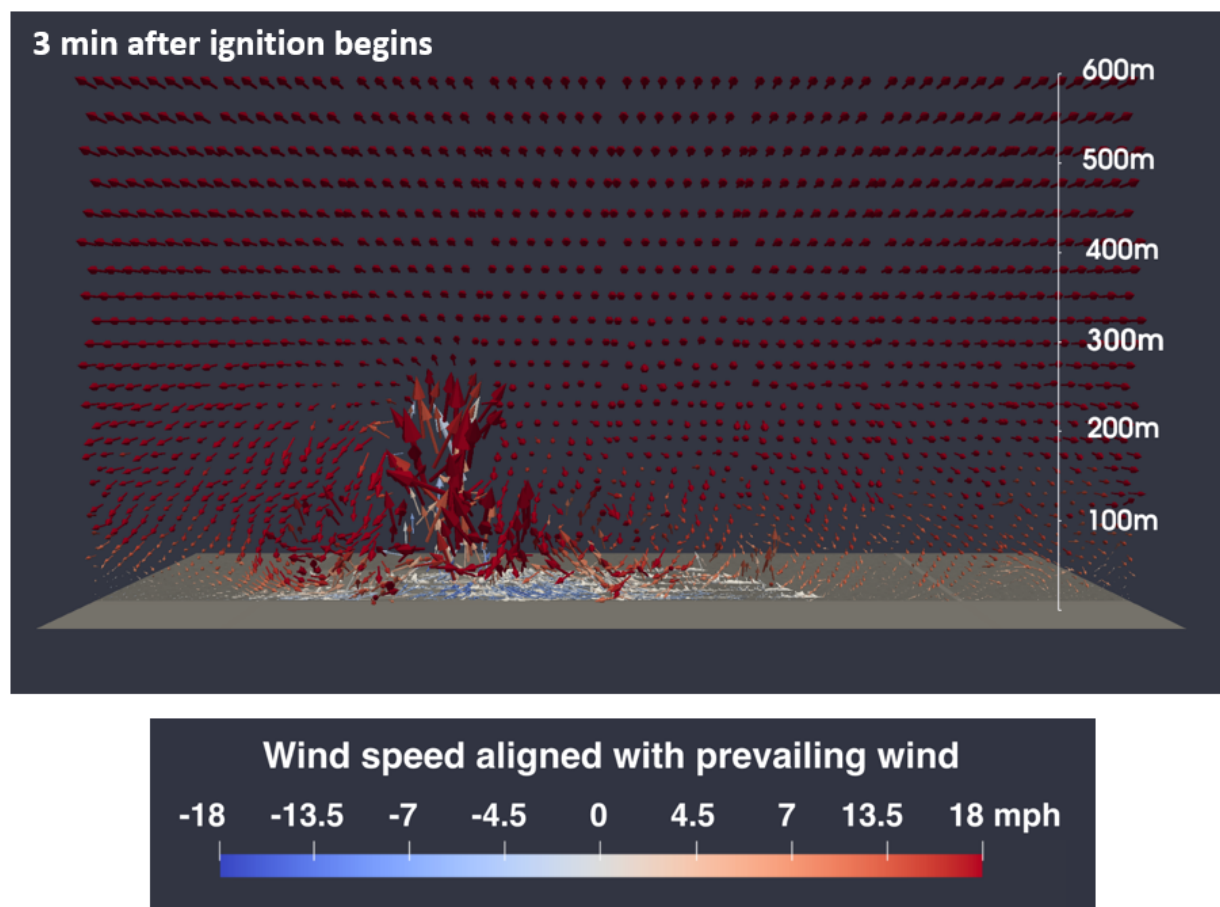


Fig. 47. 5-line ATV ignition with 5mph winds; focus on winds through a vertical slice.

In the facilitated workshops mentioned above, the project team presented project results and administered Likert survey questionnaires to thirty-six wildland fire managers and practitioners concerning the usefulness of physics-based modeling efforts for enhancing fire managers' knowledge, skills and abilities. For knowledge enhancement to be considered a success, greater than 80% of workshop participants and end users had to respond that they "agree" or "strongly agree" that the FIRETEC model demonstration improved their understanding of prescribed fire ignition techniques and resulting fire behavior. The success criteria was easily met as ninety-seven percent submitted that they "agree" or "strongly agree" (61% strongly agree) that *"Current prescribed fire practitioner training could be improved using visual products, data and lessons learned from this FIRETEC project."* Eighty-seven percent of attendees "agree" or "strongly agree" that *"The FIRETEC model demonstration improved my understanding of prescribed fire ignition techniques and resulting fire behavior."* To the question, "On a scale of 1 (definitely will not) to 10 (definitely will), how likely are you to use information from this workshop?" average score was 8.44. The complete Likert survey form used at the practitioner workshops, with cumulative results highlighted, can be found in Appendix D.

7.0 COST ASSESSMENT

It must be understood when assessing implementation costs for end users that the FIRETEC model will likely never be operated by fire managers on their desktop computers. This was never the focus of this project. What *will* be used are the innovative and realistic training tools and curriculum that FIRETEC, through this project, has been instrumental in developing. The techniques developed and lessons learned from this project will significantly expedite and reduce costs for similar FIRETEC projects in the future. It is important to note that there is currently no known alternative method for producing the type of visual, site, and weather specific training curriculum that can be developed using FIRETEC model runs.

7.1 COST MODEL

Table 5. Cost Model

Table 5. Cost Model for FIRETEC Demonstration & Tech. Transfer		
Cost Element	Data Tracked During Demonstration	Approx. Costs for Similar Future Efforts
RxCADRE data analysis & compilation	\$220K	\$50K
FIRETEC simulations & analysis:	—	—
>RxCADRE	\$280K	\$50K
>Baseline prescribed fire scenarios	\$200K	\$80K
>Phenomenology Study	\$200K	\$80K
White Paper, report, curriculum & publication development	\$100K; Not tracked (Air Force and Army contributed time)	\$100K
LANL supercomputer access	Not tracked	

7.2 COST DRIVERS

This project forced an expansion of the way that FIRETEC had been used in the past. For example, substantial data analysis was required in order to compare FIRETEC to specific fires in marginal burning conditions, something that had never been done before. Due to the marginal

burning conditions of the RxCADRE fires, which are not unlike those of many prescribed fires, there were significant unforeseen challenges due to the increased sensitivity of the fire to transient and heterogeneous conditions. Related to this, there were significant costs associated with the development of techniques to prepare the input data for simulations and analyze what was a much more complicated set of results than expected. However, many lessons were learned through the course of this project and new data processing techniques were honed, reducing the costs of data analysis and simulation initialization for similar efforts in the future. It should, however, be kept in mind that the destructive field sampling and experimental fires were performed outside of this project and can be significant undertakings. To determine accuracy/validity of this technology *to the same degree* as this project, but in differing fuel types, terrain, and weather conditions, would require fuels and wind data collection for the fuel and weather conditions that are of most value/interest to fire managers in that region, as was done with the RxCADRE experiments. This would likely entail significant additional costs beyond modeling alone.

A key factor affecting the cost of utilizing this technology for future users is the purpose for which it is being used. For developing realistic visual images of fire behavior in specific terrain and fuel types from a single ignition point (typical of a wildfire) to assist with training entry level firefighters, FIRETEC could be utilized without having data derived from an actual fire. Thereby, the only costs would be for LANL's staff time, practitioner oversight (co-produced materials) and supercomputer time, plus curriculum development if a specific course is being developed. For more advanced training and/or planning tools for prescribed fire managers, Incident Commanders, and disaster preparedness professionals, more accuracy and hence, more detailed input data would be desirable, driving the cost up significantly. If this technology was to be used to develop for training materials and/or for planning purposes, there would be a sliding scale of cost ranging from less than \$10,000 to more than \$300,000 depending on the audience and breadth of scenarios to be illustrated. Deploying the technology from this project through use of the cutting-edge training tools will be essentially free to the end user since training is a normal part of a fire manager's job.

8.0 IMPLEMENTATION ISSUES

From the standpoint of the wildland fire community, there are no issues with implementation of this project's simulations and data for training use. In fact, there has been significant enthusiasm and acceptance of FIRETEC's value for this purpose as illustrated by the Likert survey responses from wildland fire experts attending the workshops associated with this project (Appendix D). As one example, after one viewing of the project results the National Interagency Prescribed Fire Training Center immediately agreed to integrate simulations and data from this project into their national curriculum. However, the ability for fire managers to use physics-based fire behavior models on their office computers for daily operational planning is still a few years away due to the computational requirements of advanced models such as FIRETEC. It is worth noting, however, that this project is serving as a springboard towards this end by, 1) highlighting the shortcomings of currently available operational fire behavior models to the wildland fire community, thereby creating enthusiasm/demand for these next-generation physics-based models, 2) providing a robust data set that can be used by simpler, less computationally intensive models (currently under development) for comparison with FIRETEC results, 3) informing the design of future large-scale

fire experiments similar to RxCADRE to collect more useful data for fire modelers, 4) showcasing the positive outcomes possible with “co-production” between fire scientists, fire modelers and fire practitioners, and, 5) advancing the concept of “prescribed fire science”, as a separate branch of fire science worthy of investment.

That being said, rigorous statistical validation based on replication is not feasible for any fire behavior model given the fact that it is impossible to burn the same area multiple times under the exact same conditions for comparison with model results. There are simply too many ever changing variables (e.g. time of day, time of year, time since last fire, fuel moisture, fuel loading, fuel continuity, temperature, time since last rain, amount of last rain, drought index, atmospheric stability, wind speed, wind direction, ignition technique, etc.). The project addressed this challenge in a number of ways. Data generated from the S5 RxCADRE burn and FIRETEC were analyzed in a number of innovative ways as described in Sections 6.1 and 6.2. Additionally, prescribed fire practitioner-experts were used to formally evaluate project results via the Likert surveys mentioned above.

9.0 REFERENCES

Achtemeier, G.L., Goodrick S.A., and Liu Y. (2012) *Modeling Multiple-Core Updraft Plume Rise for an Aerial Ignition Prescribed Burn by Coupling Daysmoke with a Cellular Automata Fire Model*. Atmosphere 3, 352-376. doi: 10.3390/atmos3030352.

Alexander, M. E. and M. G. Cruz. 2013. “Are the applications of wildland fire behaviour models getting ahead of their evaluation again?” Environmental Modeling and Software 41:65-71.

Bossert J. E., Linn R.R., Reisner J.M. , Winterkamp J. L., Dennison P., Roberts D. (2000) *Coupled atmosphere-fire behavior model sensitivity to spatial fuel characterization*. In ‘Proceedings of the Third Symposium on Fire and Forest Meteorology’, January 2000.p.21. (American Meteorological Society: Long Beach, CA)

Bradley M. M. (2002) *This model can take the heat*.
<http://www.llnl.gov/str/November02/Bradley.html>

Cassagne N., Pimont F., Dupuy J-L., Linn R. R., Marels A., Olivieri C, Rigolot R. (2011) *Using a fire propagation model to assess the efficiency of prescribed burning in reducing the fire hazard*. Ecological Modeling 222, 1502-1514.

Canfield J.M., Linn R.R., Sauer J.A., Finney M., J. Forthofer (2014) *A numerical investigation of the interplay between fireline length, geometry, and rate of spread*, Agricultural and Forest Meteorology, 189–190(1): 48-59.

Cheney, N.P., Gould, J.S., Catchpole, W.R. (1993) *The influence of fuel, weather and fireshape variables on fire-spread in grasslands*. International Journal of Wildland Fire 3, 31–44.

Clark M. M., Fletcher T. H., Linn R. R. (2010) *A sub-grid, mixture-fraction-based*

thermodynamic equilibrium model for gas phase combustion in FIRETEC: Development and results. International Journal of Wildland Fire.

Clements CB, Lareau N, Seto D, Contezac J, Davis B, Teske C, Thomas J. Zajkowski ^{C D}, Andrew T. Hudak ^E, Benjamin C. Bright ^E, Matthew B. Dickinson ^F, Bret W. Butler ^G, Daniel Jimenez ^G and J. Kevin Hiers ^H (2016) *Fire weather conditions and fire-atmosphere interactions observed during low-intensity prescribed fires – RxCADRE 2012.* International Journal of Wildland Fire 25(1) 90-101 <https://doi.org/10.1071/WF14173>

Cunningham P., Linn R. R. (2007) *Numerical simulations of grass fires using a coupled atmosphere-fire model: Dynamics of fire spread.* J. Geophys. Res., 112, D05108, doi: 10.1029/2006JD007638

Davis, Aika Y., R. Ottmar, Y. Liu, S. Goodrick, G. Achtemeier, B. Gullett, J. Aurell, W. Stevens, R. Greenwald, Y. Hu, A. Russell, J. K. Hiers, T. Odman. 2015. *Fire emission uncertainties and their effect on smoke dispersion predictions: a case study at Eglin Air Force Base, Florida, USA.* International Journal of Wildland Fire 24.2 (2015): 276-285.

Dupuy J-L., Linn R. R., Konovalov V., Pimont F., Vega J. A., Jimenez E. (2011) *Exploring coupled fire/atmosphere interactions downwind of wind-driven surface fires and their influence on backfiring using the HIGRAD-FIRETEC model.* International Journal of Wildland Fire.

Hiers J.K., O'Brien J.J., Will R.E., and Mitchell R.J. (2007). *Forest Floor Mediates Understory Vigor in Xeric Pinus Palustris Ecosystems.* Ecological Applications, 17 (3): pp. 806-814.

Hoffman CM., Canfield J, Linn RR, Mell W, Sieg CH, Pimont F, Ziegler J. (2015), *Evaluating crown fire rate of spread predictions from physics-based models,* Fire Technology 52 (1), 221-237.

Hudak, Andrew T., Matthew B. Dickinson, Benjamin C. Bright, Robert L. Kremens, E. Louise Loudermilk, Joseph J. O'Brien, Benjamin S. Hornsby, and Roger D. Ottmar. *Measurements relating fire radiative energy density and surface fuel consumption–RxCADRE 2011 and 2012.* International Journal of Wildland Fire 25, no. 1 (2016): 25-37.

Linn R. R. (1997) *Transport model for prediction of wildfire behavior.* Los Alamos National Laboratory, Scientific Report LA13334-T

Linn, R. R., Cunningham, P. (2005) *Numerical simulations of grass fires using a coupled atmosphere-fire model: basic fire behavior and dependence on wind speed.* Journal of Geophysical Research-Part D-Atmospheres 110(D13).

Linn R. R., Reisner J. M., Colman J. J., Winterkamp. J. L. (2002) *Studying wildfire behavior using FIRETEC.* International Journal of Wildland Fire 11, 233-246. doi: 10.1071/WF02007

Linn R. R., Reisner J. M., Edminster C. B., Harlow F., Winterkamp J. L., Bossert J. E., White A., Smith W. S., Colman J. J. (2003) *FIRETEC - A physics-base wildfire model*. Los Alamos National Laboratory, USDA Forest Service, Rocky Mountain Research Station, 2003 R&D 100 Joint Entry, Los Alamos, NM, 2003.

Linn R. R., Cunningham P. (2005) *Numerical simulations of grass fires using a coupled atmosphere-fire model: Basic fire behavior and dependence on wind speed*. J. Geophys. Res., 110, D13107, doi:10.1029/2004JD005597

Linn R. R., Winterkamp J. L., Colman J. J., Edminster C. B., Bailey J. D. (2005a) *Modeling interactions between fire and atmosphere in discrete element fuel beds*. International Journal of Wildland Fire 14, 37-48. doi: 10.1071/WF04043

Linn R. R., Canfield J. M., Cunningham P., Edminster, C., Dupuy J-L., Pimont F. (2012b) *Using periodic line fires to gain a new perspective on multi-dimensional aspects of forward fire spread*. Agricultural and Forest Meteorology 157, 60-76. doi: 10.1016/j.agrformet.2012.01.014

Linn R. R., Canfield J., Winterkamp J. L., Cunningham P., Colman J. J., Edminster C. B., Goodrick S. (2005b) *Numerical simulations of fires similar to those of the International Crown Fire Modeling Experiment*. In 'Proceedings of the Sixth Symposium on Fire and Forest Meteorology', October 2005, Canmore, Alberta, Canada.

Linn R. R., Winterkamp J. L., Edminster C. B., Colman J. J., Smith W. S. (2007) *Coupled influences of topography and wind on wildland fire behaviour*. International Journal of Wildland Fire 16, 183-195. doi: 10.1071/WF06078

Linn R. R., Winterkamp J. L., Weise D. R., Edminster C. B. (2010) *A numerical study of slope and fuel structure effects on coupled wildfire behavior*. International Journal of Wildland Fire 19, 179-201 doi: 10.1071/WF07120

Linn R., Anderson K., Winterkamp J., Brooks A., Wotton M., Edminster C., Dupuy J-L., Pimont F. (2012a). *Incorporating field wind data into FIRETEC simulations of the International Crown Fire Modeling Experiment (ICFME): preliminary lessons learned*. Canadian Journal of Forest Research 42(5): 879-898, <http://dx.doi.org/10.1139/X2012-038>.

Linn R, Sieg C. H., Winterkamp, Parsons R., and Hoffman C. (2011) *Examining Mountain Pine Beetle Impacts on Coupled Fire/Vegetation/Atmosphere Behavior in Lodgepole Pine Stands Using FIRETEC*. Ninth Symposium on Fire and Forest Meteorology, October 18, 2011 (American Meteorological Society: Palm Springs, CA)

Linn R. R., Canfield J. M., Cunningham P., Pimont F., Dupuy J-L., Edminster C. B. (2012a) *Using periodic line fires to gain a new perspective on multi-dimensional aspects of forward fire spread*, Agricultural and Forest meteorology.

- Linn R. R., Winterkamp J. L., Colman J. J., Edminster C. B., Bailey J. D. (2005) *Modeling interactions between fire and atmosphere in discrete element fuel beds*. International Journal of Wildland Fire 14, 37-48. doi: 10.1071/WF04043
- Linn R. R., Winterkamp J. L., Colman J. J., Edminster C. B., Bailey J. D. (2005) *Modeling interactions between fire and atmosphere in discrete element fuel beds*. International Journal of Wildland Fire 14, 37-48. doi: 10.1071/WF04043
- Mell, W., M. A. Jenkins, J. Gould, and P. Cheney. (2007) *A physics-based approach to modelling grassland fires*. International Journal of Wildland Fire 16:1-22.
- Mueller E, Mell W, Simeoni A (2014) *Large eddy simulation of forest canopy flow for wildland fire modeling*. Can J For Res 44:1534–1544
- O'Brien, J. J., E. L. Loudermilk, B. Hornsby, A. T. Hudak, B. C. Bright, M. B. Dickinson, J. K. Hiers, C. Teske, and R. D. Ottmar. 2016. *High-resolution infrared thermography for capturing wildland fire behaviour: RxCADRE 2012*. International Journal of Wildland Fire 25 (1): 62-75.
- Ottmar, Roger D., Hudak, Andrew T., Prichard, Susan J., Wright, Clinton S., Restaino, Joseph C., Kennedy, Maureen C., Vihnanek, Robert N. (2016) *Pre-fire and post-fire surface fuel and cover measurements collected in the southeastern United States for model evaluation and development – RxCADRE 2008, 2011 and 2012*. International Journal of Wildland Fire **2016**, 25, 10–24 <http://dx.doi.org/10.1071/WF15092>
- Overholt KJ, Kurzwski AJ, Cabrera J, Koopersmith M, Ezekoye OA (2014a) *Fire behavior and heat fluxes for lab-scale burning of little bluestem grass*. Fire Saf J 67:70–81
- Overholt KJ, Cabrera J, Kurzwski A, Koopersmith M, Ezekoye OA (2014b) *Characterization of fuel properties and fire spread rates for little bluestem grass*. Fire Technol 50(1):9–38
- Parsons R. (2007) *Spatial variability in forest fuels: Simulation modeling and effects on fire behavior*. Forestry Dept., University of Montana (PhD Dissertation.)
- Peet R. K., Wentworth T.R., White P.S. (1998). *A flexible multipurpose method for recording vegetation composition and structure*. Castanea, 63 (3): pp 262-274.
- Pimont, F., Linn, R.R., Dupuy, J-L., Morvan, D. (2006). *Effects of vegetation description parameters on forest fire behavior with FIRETEC*. Forest Ecology and Management 234S(S120).
- Pimont F., Dupuy J-L., Linn R. R., and Dupont S. (2009) *Validation of FIRETEC wind-flows over a canopy and a fuel-break*. International Journal of Wildland Fire, 18(7): p. 775-790.
- Pimont F., Dupuy J-L., Linn R. R., Dupont S. (2011) *Impacts of fuel-break structure on wind-*

flows and fire propagation simulated with FIRETEC. Annals of Forest Science.

Pimont F., Dupuy J-L., Linn R. R. (2012) *Coupled slope and wind effects on fire spread with influences of fire size: a numerical study using FIRETEC* submitted to International Journal of Wildland Fire (minor revision submitted 1/2012).

Sánchez-Monroy, X., Mell W., Torres-Arenas J., Butler B.W. (2019) *Fire spread upslope: Numerical simulation of laboratory experiments*. Fire Safety Journal 108:

Sieg C. H.I, USFS, Linn R.R., Hoffman C., Winterkamp J., and McMillin J. (2011) *Coupled Fire/Atmosphere Behavior in Highly Heterogeneous Woodlands and the Impacts of Tree Mortality on Fire Spread*. ‘Ninth Symposium on Fire and Forest Meteorology’, October 18, 2011 (American Meteorological Society: Palm Springs, CA)

Smith W. S., Linn R. R., Sauer J. A., Canfield J. M., Winterkamp J. L. (2007) *HIGRAD/FIRETEC wildfire model: Description of basic theory and numerics*. Los Alamos National Laboratory, Scientific Report LA-UR-078232.

Sullivan, A. L. 2009. *Wildland surface fire spread modelling, 1990-2007. 3: Simulation and mathematical analogue models*. International Journal of Wildland Fire 18: 387-403. DOI 10.1071/WF06144

Terrei, L., Lamorlette, A., & Ganteaume, A. (2019) *Modelling the fire propagation from the fuel bed to the lower canopy of ornamental species used in wildland–urban interfaces*. International Journal of Wildland Fire, 28(2), 113-126.

Vega J.A., Jiménez E., Dupuy J.L., Linn R.R. (2012, in pres, accepted for Publication May 2012). *Seeking opportunities for backfire use in shrubland wildfire fighting in NW Spain*. International Journal of Wildland Fire.

Wade, D. D., Lunsford, J. D., Dixon, M. J., & Mobley, H. E. (1989). A guide for prescribed fire in southern forests. *Technical publication R8-TP-US Department of Agriculture, Forest Service, Southern Region (USA)*.

APPENDIX A: Points of Contact

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone Fax E-mail	Role in Project
James H. Furman	USDA Forest Service 626 E. Wisconsin Ave. Milwaukee, WI 53202	850-978-3236 James.h.furman@usda.gov	PI
Dr. Rodman Linn	Los Alamos National Lab	505-500-2602 rrl@lanl.gov	Co-PI
Brett W. Williams	Air Force Wildland Fire Branch 107 Hwy 85 North Niceville, FL 32578	850-978-3250 Brett.williams.4@us.af.mil	Co-PI
Judith Winterkamp	Los Alamos National Lab	judyw@lanl.gov	FIRETEC Modeler

APPENDIX B – General Fuel Descriptions

Surface fuels for all scenarios:

- Fine Dead Fuel Moisture = 8%
- Fuel Loading = 0.79 kg/m² (3.5 tons/acre), evenly distributed
- Fuel Bed Depth = 0.5m (1.64'), spread uniformly

Overstory for all forested scenarios:

- Longleaf Pine (*pinus palustris*) height 11.3-23.2m (37.1'-76.1')
- Turkey oak (*Quercus laevis*) height 7.3-11.6m (23.9'-38.1')

Midstory:

- Persimmon (*Diospyros virginiana*), 223 stems/acre, height 1.5-2m (4.9'-6.6')
- Longleaf pine, 165 stems/acre, height 1.5 – 3.5m (4.9'-11.5')
- Turkey oak, 398 stems/acre, height 2-4.5m (6.6'-14.8')

“Open” Midstory: aka “Midstory Managed”, based on Eglin AFB high quality sandhills monitoring plot

- Persimmon (*Diospyros virginiana*), 223 stems/acre, height 1.5-2m (4.9'-6.6')
- Longleaf pine, 165 stems/acre, height 1.5 – 3.5m (4.9'-11.5')
- Turkey oak, 18 stems/acre, height 2m (6.6')

“Wet”: Used to denote leaf on/growing season fuel moistures

- Persimmon = 170%
- Longleaf pine = 133%
- Turkey oak = 200%

“Dry”: Used to denote dormant season fuel moistures

- Longleaf pine = 133%
- Turkey oak = 15%

APPENDIX C – Estimating Fire Effects: Relative Consumption

Baseline Scenario Consumption						
Ignition Scenario	# lines	Fuel type	Understory	Midstory	Canopy	Combined Midstory/Canopy
5mph atv	1	Ground	0.91	0	0	0
5mph atv	1	Canopy, dry	0.91	0.89	0.06	0.1
5mph atv	1	Midstory, dry	0.93	0.89	0.17	0.33
5mph atv	2	Midstory, dry	0.93	0.89	0.2	0.35
5mph atv	4	Midstory, dry	0.94	0.89	0.21	0.36
5mph atv	6	Midstory, dry	0.94	0.89	0.26	0.4
12mph atv	1	Ground	0.93	0	0	0
12mph atv	1	Canopy, dry	0.93	0.91	0.07	0.11
12mph atv	1	Midstory, dry	0.94	0.9	0.26	0.4
12mph atv	2	Midstory, dry	0.95	0.91	0.28	0.42
12mph atv	4	Midstory, dry	0.95	0.91	0.26	0.41
12mph atv	6	Midstory, dry	0.96	0.91	0.34	0.47
5mph aerial	5	Midstory, dry	0.91	0.81	0.12	0.28
5mph aerial	10	Midstory, dry	0.93	0.85	0.13	0.29
5mph aerial	15	Midstory, dry	0.92	0.83	0.13	0.29
12mph aerial	5	Midstory, dry	0.96	0.9	0.15	0.32
12mph aerial	10	Midstory, dry	0.96	0.9	0.15	0.32
12mph aerial	15	Midstory, dry	0.96	0.9	0.16	0.32
		Height	0-1.5m	1.5-4.7m	4.7-23.0m	1.5-23.0m

Phenomenology Study Consumption				
Ignition Scenario	Understory	Midstory	Canopy	Combined Midstory/Canopy
5mph closed flank	0.94	0.89	0.3	0.43
5mph strip	0.94	0.89	0.26	0.4
5mph open, wet strip	0.91	0.71	0.06	0.14
5mph 14m dash	0.93	0.85	0.12	0.28
5mph 6m dash	0.93	0.84	0.11	0.27
5mph aerial	0.93	0.84	0.12	0.28
5mph staggered aerial	0.92	0.82	0.09	0.25
12mph closed flank	0.95	0.91	0.33	0.45
12mph strip	0.95	0.91	0.31	0.44
12mph open, wet strip	0.94	0.78	0.05	0.14
12mph 14m dash	0.96	0.9	0.17	0.33
12mph 6m dash	0.96	0.9	0.16	0.32
12mph aerial	0.96	0.89	0.13	0.3
12mph staggered aerial	0.96	0.89	0.16	0.32
Height	0-1.5m	1.5-4.7m	4.7-23.0m	1.5-23.0m

APPENDIX D. 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!