FINAL REPORT

Title: Fire and Smoke Model Evaluation Experiment (FASMEE)—Phase 2

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List of Abbreviations and Acronyms

ALS	Airborne Laser Scanning
BB-FLUX	Biomass Burning Flux Measurements of Trace Gases and Aerosols
CAWFE	Atmosphere-Wildland Fire Environment model
Consume	Model for predicting fuel consumption and emissions
COVID	Coronavirus disease
Daysmoke	Empirical-statistical plume-rise and dispersion model
DBH	Diameter at Breast Height
dBZ	Decibel relative to Z. Logarithmic dimensionless technical unit used in radar
dNBR	Delta Normalized Burn Ratio
DoD	Department of Defense
eMAS	Enhanced MODUS Airborne Simulator
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
FASMEE	Fire and Smoke Model Evaluation Experiment
FB&E	Fire Behavior and Energy
FCCS	Fuel Characteristic Classification System
FFT	Fuel and Fire Tools
FIA	Forest Inventory Assessment
FIRETEC	Physics-based computational fire behavior model
FIREX	Fire influence on regional and global environments experiment (National Atmospheric and Oceanic Administration)
FIREX-AQ	Fire influence on regional and global environments experiment – air quality (National Aeronautics and Space Administration)
FlamMap	Fire behavior mapping and analysis program that computes potential fire behavior characteristics
FOFEM	First Order Fire Effects Model
FRE	Fire Radiative Energy
FRP	Fire Radiative Power
FUSION	LiDAR analysis and visualization software
G-LiHT	Goddard's LiDAR, Hyperspectral and Thermal Imager
HYSPLIT	Simple air parcel trajectory model
IR	Infrared
JFSP	Joint Fire Science Program
JPL	Jet Propulsion Laboratory
KASPR	Ka-band Scanning Polarimetric Radar
LANDFIRE	Landscape Fire and Resource Management Planning Tools
lidar	Light imaging, detection and ranging
MesoNH-ForeFire	Mesoscale atmosphere model
MODUS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NRS	Northern Research Station
NF	National Forest
NOAA	National Oceanic and Atmospheric Administration
NOI	Notice of Intent

NSF	National Science Foundation
phv	V-polarization signals from radar
PLS	Partial Least Square Regression
PM	Particulate Matter
PNW	Pacific Northwest
PNWRS	Pacific Northwest Research Station
RMRS	Rock Mountain Research Station
RxCADRE	Prescribed fire Combustion Atmospheric Dynamics Research Experiment
SEMIP	Smoke and Emissions Model Inter-comparison Project
SERDP	Strategic Environmental Research and Development Program
SRS	Southern Research Station
SW	Southwest
TLS	Terrestrial Laser Scanner
UAS	Unmanned aircraft systems
USGS	United States Geological Service
WE-CAN	Western wildfire Experiment for Cloud chemistry, Aerosol absorption, Nitrogen
WFDS	Wildland-urban interface Fire Dynamics Simulator
WRF	Weather Research Forecasting model
WRF-SFIRE	Combination of the weather research and forecasting model (WRF) with a fire code invoking a surface fire behavior model (open source)
WWC	Western Wildfire Campaign
ZDR	Differential phase shift related to radar output

Keywords

Smoke modeling, fire modeling, large fire experiments, fuel, fuel consumption, fire behavior, energy release, plume rise, smoke transport and dispersion, smoke chemistry, fire effects, soil heating

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Abstract

The Joint Fire Science Program (JFSP) and the Environmental Security Technology Certification Program (ESTCP) initiated the Fire and Smoke Model Experiment (FASMEE) (https://fasmee.net) by funding JFSP Project 15-S-01-01. This nationwide, multiagency effort identifies and collects critical measurements that will be used to advance fire and smoke science and modeling capabilities, allowing managers to 1) increase the use of managed fire, 2) improve firefighting strategies, 3) enhance smoke forecasts, 4) better assess carbon stores and fire-climate interactions and improve our understanding of other fire effects such as vegetation response. FASMEE also provides unparalleled opportunities to introduce new technology and the next generation of fire researchers in the largest coordinated fire project to date. The core leadership portioned FASMEE into three phases including analysis and planning (Phase 1), data collection (Phase 2), and future improvements (Phase 3). Phase 1 is complete, with the study plan as the main deliverable and a final report submitted and accepted by the JFSP in 2020. The plan includes science questions, data measurements and specifications, and burn recommendations that serve to guide planning. The plan has been published in the scientific literature.

FASMEE embarked on Phase 2 with the initial and continued support of the JFSP and additional funding from the US Forest Service Pacific Northwest Research Station and the Washington Office Fire and Aviation Management. These funds were leveraged with several other agency resources including National Science Foundation (NFS), National Oceanic and Atmospheric Administration (NOAA) and National Aeronautics and Space Administration (NASA) to successfully embark on the western wildfire campaign and southwest campaign, two of three data collection campaigns identified in the FASMEE study plan, Phase 2.

The western wildfire, southwest and southeast campaigns were initiated in 2018 to commence the data collection of Phase 2. For the western wildfire campaign, fuel maps were developed based on airborne LiDAR, initial field data collection, and modeled source characterization for wildfires flown by the National Science Foundation supported WE-CAN and BB-FLUX projects in 2018 and NOAA and NASA FIREX-AQ project in 2019 were completed. Data collection for 3 large stand replacement fires on the Fishlake National Forest including Manning Creek, Langdon Mountain, and Annabella were completed for the southwestern campaign. Initial planning for the southeast campaign at Fort Stewart Georgia has also begun. Specific deliverables for this JFSP project include:

1) Provided overall leadership of FASMEE during the planning and data collection Phase 1 and 2.
2) In conjunction with JFSP, leveraged FASMEE with other partners including SERDP, US Forest Service, NSF, NOAA, NASA, and EPA;
3) Completed, submitted, and distributed a FASMEE study plan that was published in the peer reviewed literature followed by a Phase 1 final report that was approved by the JFSP;
4) Developed a LiDAR fuels map and modeled the source characterization of wildfires flown for smoke measurements by the WE-CAN, BB-FLUX, and FIREX-AQ projects in 2018 and 2019 as part of Phase 2 Western Wildfire Campaign data collection campaign;
5) Completed data collection and preliminary data reduction for 6 research discipline area on the Manning Creek, Langdon Mountain, and Annabella stand replacements fires for the Phase 2 southwest data collection campaign.
6) Initiated planning for data collection during the southeast campaign at Fort Stewart.

1. Objectives

Fire and smoke models are critical tools for wildland fire decision-making and planning. However, many models that currently drive the operational systems in use today lack suitable foundational data, thereby compromising their reliability (Alexander and Cruz 2013, Cruz and Alexander 2010). As a consequence, the limits of applicability and expected errors are not defined for many models, and their use may not be realistic under specific conditions (Yao et al. 2014). Accurate estimates of fire and smoke emissions and dispersion from wildland fires are highly dependent on reliable characterization of many variables including: area burned, preburn biomass of fuelbed components and condition, fuel consumption by combustion phase, fire behavior, heat-release, plume dynamics, meteorology, and smoke chemistry. Improving estimates of plume rise, smoke production, and dispersion are fundamentally based on characterizing fire-atmosphere interactions, including fuel conditions, wildland fire behavior, and smoke plume dynamics. The Fire and Smoke Model Evaluation Experiment (FASMEE) (https://fasmee.net) is designed as a large-scale, multi-agency study to fulfill the need for foundational data for fire and smoke modeling by identifying and collecting critical measurements. The aim is to advance wildland fire science and modeling capabilities for improved suppression operations and increased use of managed fire.

The overall goal of FASMEE is to evaluate and advance operationally applicable fire and smoke modeling systems and their underlying scientific models and frameworks. The main objective of this final report, is to provide an update and progress of the field data collection effort for the western Wildfire, southwest and southeast field campaigns as part of Phase 2.

To meet this goal, three major sub-objectives were identified:

- Collect, reduce, and make available a set of quality-controlled and integrated measurements during Phase 2 as outlined in the Phase 1 study plan;
- Assure data quality, access, and value with proper data collection, management, and organization within an appropriate data access system; and
- Use data collected during the observational campaigns to improve and expand operational fire and smoke modeling.

As outlined in the study plan, FASMEE was partitioned into three phases:

- Phase 1—The analysis and planning process to review and assess the current state of fire-plume-smoke modeling and scientific understanding to determine the critical needs and realistic pathways to addressing these needs.
- Phase 2—Implementation of a set of three field campaigns (Western Wildfire Campaign, Southwest Campaign, and Southeast Campaign) to be completed over 2019-2022 to collect data valuable for model evaluation and improvement.
- Phase 3, Future Improvements—Identified set of analyses and improvements to models based on the data

The main deliverable of Phase 1 was the development of the FASMEE study plan (Ottmar et al. 2017) along with a Notice of Intent and Funding Opportunity Notice. The research effort was funded by JFSP and Department of Defense (DoD)'s Environmental Security Technology Certification Program (ESTCP). Following the design outlined in the study plan, the Phase 2 Western Wildfire and southwest campaigns were initiated as "additional work" under the 15-S-01-01 agreement with JFSP. This additional work was funded and supported by the JFSP, USDA Forest Service, and EPA, along with in-kind support from the NOAA and NASA FIREX-AQ project in 2018 through 2021.

Pre-planning for the southeast campaign at Fort Stewart, GA scheduled for March, 2022, was also undertaken. FASMEE was presented at several conferences, symposia and Rx training venues during 2016-2021, and results were documented in two research articles (Liu et al. 2019, Prichard et al. 2019). Prichard et al. (2019) presented an overview of FASMEE and discussed the need for FASMEE for motivating improvement in fire and smoke modeling capability for both science and operational application. Liu et al. (2019) presented the modeling activities conducted in Phase 1 to identify major fire behavior and smoke modeling issues and the most critical observational measurements to fill modeling gaps. These papers, along with other peer reviewed and grey literature, wildland fire training courses, and media coverage provide comprehensive documentation of this unique and valuable project.

The FASMEE project was conceived and initiated with guidance from the Joint Fire Science Program (JFSP) smoke science plan (Riebau and Fox 2010), a JFSP-sponsored smoke workshop synthesis, and the success of the Prescribed Fire Combustion and Atmospheric Dynamic Research Experiment (RxCADRE). By directly and indirectly influencing improvements to operational fire and smoke models, results from FASMEE will guide:

- The land management community, through improved models and guidance on their performance, reliability, scope of applicability, and validation;
- The scientific community, through a unique dataset and new understanding of fire, fire effects, emissions, and smoke plumes, chemistry, and transport; and
- The public, through improved fire information and smoke impact warnings.

This final report provides a brief review of the FASMEE project planning and design process to develop the studies concept and science plan. The main emphasis will be to provide progress on data collection and wildfire source modeling that was part of the Phase 2 Western Wildfire and Southwest Campaign data collection. Specific progress to date as presented in this final report include:

- Development of a LiDAR fuels map and model the source characterization of wildfires flown for smoke measurements by the WE-CAN, BB-FLUX, and FIREX-AQ projects in 2018 and 2019 as part of the FASMEE Western Wildfire Campaign data collection (data reduction completed and distributed to WE-CAN and BB-Flux leads; FIREX-AQ LiDAR map distributed with fuel data reduction)
- Collection of fire data for 6 research discipline areas including fuels, fire behavior, energy, plume dynamics, smoke, and vegetative fire effects during 3 large stand replacement research burns (Manning Creek, Langdon Mountain, Annabella Reservoir) on the Fishlake National Forest in Utah in 2019 and 2020.
- Technology transfer of campaign and data collection through training, publications, workshops, and conferences.

2. Background and Context

Model scenarios are used across the spectrum of operational activities in managing wildland fire. Area burned (observations, airborne and satellite imagery interpretation), fuel loading (FCCS), fuel consumption (Consume and FOFEM), fire behavior (Behave and FlamMap), smoke transport (Hybrid Single Particle Lagrangian Integrated Trajectory Model [HYSPLIT]) and dispersion modeling (BlueSky Playground) systems span a broad range of complexity and sophistication (Achtemeier et al. 2011; Andrews et al. 2005, Briggs 1969, 1971, 1972; Larkin et al. 2010; Prichard et al. 2007; Reinhardt et al. 1997, Stein et al. 2015). Complex physics-based smoke models include fire and atmosphere dynamics that drive buoyancy-induced plume rise and smoke transport. Currently, a number of fire weather forecasting models including WRF-SFIRE (Mandel et al. 2011; 2014), MesoNH-ForeFire (Filippi et al. 2009) and CAWFE (Cohen 2013; Cohen and Schroeder 2013) use simplified fire spread models and local smoke models such as Daysmoke (Achtemeier et al. 2011) to approximate the sources of heat and mass that generate the buoyant plume and smoke. These models resolve plume dynamics but parametrize combustion-related processes to enable faster than real-time simulations of landscape scale (thousands of ha) wildland fires at resolutions of hundreds of meters. In contrast, models such as WFDS (Mell et al. 2007) and FIRETEC (Linn et al. 2002) and even the simplified QUIC-Fire (Linn et al. 2020) explicitly account for the processes of gas-phase combustion and vegetation consumption in addition to plume rise and smoke generation. Computational fluid dynamics models of fire-atmosphere interactions require relatively high-resolution computational three-dimensional grid cells, and the resulting high computational demand precludes their routine use on large domains.

The performance of both currently used and next-generation models need to be assessed and evaluated. This assessment will make it possible to set expectations for how well a model will perform under real-world applications, the level of model uncertainties, and the key sources of these uncertainties that need improvement. This has been highlighted in recent synthesis reports, including the Joint Fire Science Program (JFSP) Smoke Science Plan (Riebau and Fox 2010), the Smoke and Emissions Model Intercomparison Project (SEMIP) (Larkin et al. 2012), the Fire and Smoke Model Evaluation workshop and report (Brown et al. 2014), a special session on Wildland Fire Behavior and Smoke (Prichard and Ottmar 2013), the Prescribed Fire Combustion Atmospheric Dynamics Research Experiment (RxCADRE) special issue (Ottmar et al. 2016) and the joint National Aeronautics and Space Administration (NASA) and National Oceanic and Atmospheric Administration (NOAA) Fire Influence on Regional to Global Environments and Air Quality (FIREX-AQ) white paper (Warneke et al. 2018). Successful collaborations in past field campaigns, including RxCADRE and the Department of Defense’s (DoD) Strategic Environmental Research and Development Program (SERDP)-funded fine-scale combustion studies, led to the JFSP partnering with the DoD Environmental Security Technology Certification Program (ESTCP) to initiate the FASMEE planning phase (Phase 1).

FASMEE has been developed as an integrative research effort to collect a large set of observational data to evaluate and improve the scientific understanding of wildland fire and smoke models and the associated science. This large-scale interagency effort is focused on the development and evolution of modeling tools serving land and fire management needs. Essential model advancements are central to operational decisions relating to (1) fire growth and fire danger, (2) fuels consumption and emissions and other fire effects, (3) plume development and characterization, (4) smoke and other fire effects. Improvements in the underlying understanding and overall accuracy of fire, smoke, and other fire effects models have been repeatedly identified as important needs in the JFSP Smoke Science Plan (Riebau and Fox 2010). Other studies, such as the Smoke and Emissions Model Intercomparison Project SEMIP (Larkin et al. 2012), show that significant improvements in these areas will require novel, integrated, observational datasets that could be used to evaluate and test models and basic understanding of processes across many different types of models needed in this work including: fuels, fire dynamics, consumption, emissions, plume rise, smoke transport, smoke chemistry and other fire effects.

3. Materials and Methods

The FASMEE concept was born out of discussions initiated in late 2014 following the successful RxCADRE campaigns. The research effort coined the Fire and Smoke Model Evaluation Experiment (FASMEE), was to be funded through JFSP and would involve discipline leaders and modelers from the start. Eight leaders, several co-leaders and four project leaders comprised the science team that reviewed and assessed the state of fire-plume smoke modeling and scientific understanding to determine critical needs and realistic pathways to address these measurement needs. The team envisioned FASMEE as a three-phase project (Fig. 1) including analysis and planning, data collection field campaign, and analysis and model improvements. Phase 1 produced the study plan, Notice of Intent, and Funding Opportunity Notice with continued leadership and final planning for Phase 2. Phase 2 is a set of field campaigns to collect data that would be completed as funding was secured. Phase 3 involves testing and improving modeling applications based on data collected in Phase 2, including recommendations for best measurement practices and a set of analyses and model improvements to inform fire and smoke management decision makers.

After an extensive search for field campaign opportunities, two regions of interest in the United States (U.S.) were selected: the West, where large, prescribed burns and wildfire opportunities are commonly available, and the Southeast, where prescribed fire is used extensively for resource management. The final selection of sites included stand-replacement prescribed fires in high-elevation mixed conifer forests on Utah's Fishlake National Forest (termed the Southwest Campaign) and low to moderate severity prescribed underburns at Georgia's Fort Stewart (the Southeast Campaign). At each site, the FASMEE leadership coordinated planning with resource managers interested in providing sites for the research purposes of FASMEE. Agency contacts expressed enthusiasm for FASMEE, making the plans viable. Even though project activities required special attention compared to typical burn operations, these resource managers found value in the planned experiment, and were willing to collaborate with researchers for a successful outcome. In 2018, a third campaign was added, called the Western Wildfire Campaign. This campaign leveraged critical smoke measurements collected on wildfires by the NFS WE-CAN and BB-FLUX efforts in 2018 and the NOAA and NASA FIREX-AQ effort in 2019 with LiDAR fuel maps and modelled source characterization provided by FASMEE, with support from JFSP.

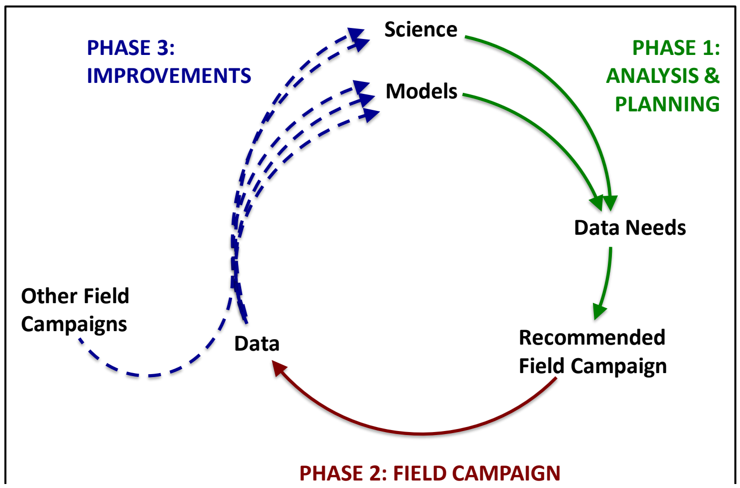


Figure 1. FASMEE phases include planning (Phase 1), observational data collection (Phase 2) and model improvements (Phase 3).

Because of the interdisciplinary nature of modeling fire and smoke, the experimental structure was divided into five science discipline areas:

- Fuels and consumption;
- Fire behavior and energy;
- Plume dynamics and meteorology;
- Smoke emissions, chemistry, and transport;
- Other fire effects (added in 2019)

These areas are necessarily integrated and interrelated, and roughly follow a logical modeling progression: fuels→fire behavior→plume dynamics→smoke chemistry→fire effects (Fig. 2).

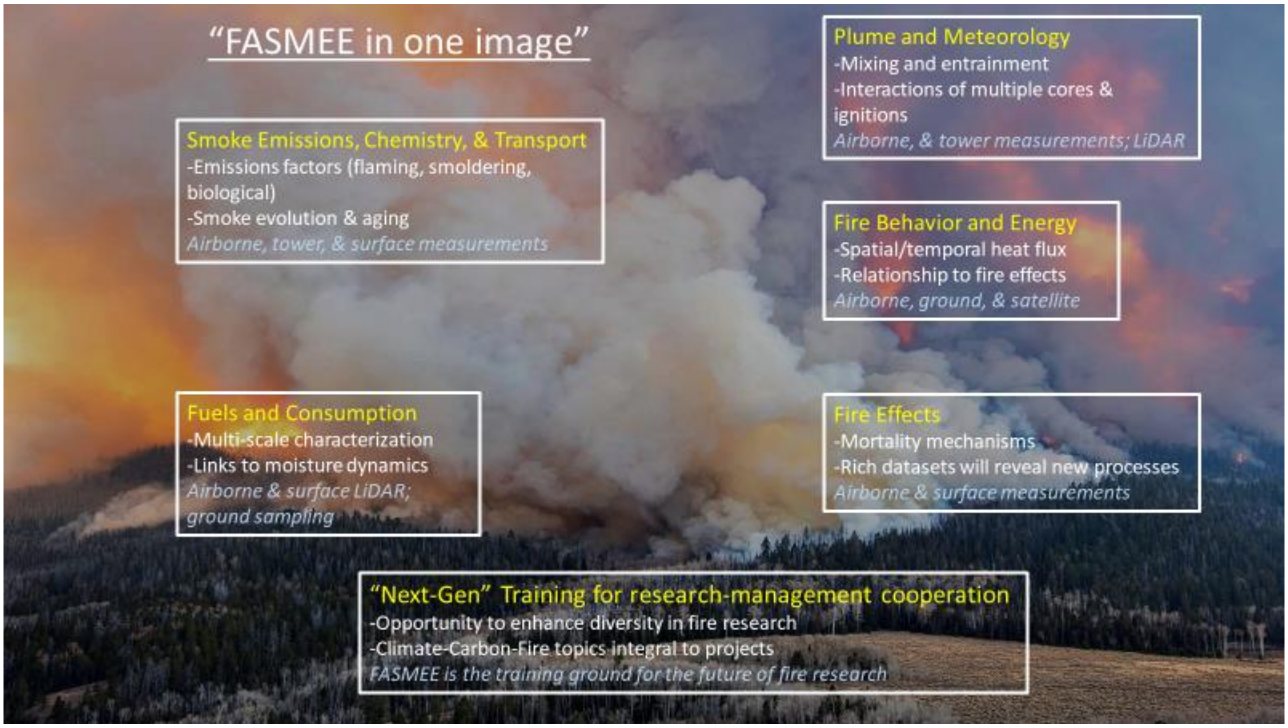


Figure 2. Graphical representation of six FASMEE research disciplines.

FASMEE focuses on a set of observational campaigns to collect, reduce, and archive critical, relevant, and comprehensive data of fire, fuels, and smoke over a range of spatial and temporal scales. These large-scale field campaigns will be used to:

- Test and validate the underlying scientific basis for fire and smoke models;
- Evaluate and advance operationally used fire and smoke modeling systems through quantification of key variables, to add capability and efficiency to these models, and to understand their domain of utility and applicability; and
- Provide observational context for continued fire and smoke model enhancement, including refinement and extension in fire regimes that have not been adequately characterized, including high-intensity fire regimes and those with complex topography

To do this, progress needs to be made to:

- Improve model parameters for both model predictions and the science that serves as the foundation for the models within operational systems. For example, field measurements will help quantify processes that drive the spatial organization of fire energy and emission, which define transitions between fires and plumes and that, ultimately, determine smoke transport.
- Add capability to models to support development of next-generation modeling systems. For example, smoke models lack a sufficient understanding of how the combustion environment combines with ambient atmospheric conditions to generate plume-driven fire dynamics.
- Improve measurements and build confidence in operational modeling capabilities and applications. This, in turn, will improve decision support for operational management.

In the end, FASMEE will be considered a success when the project:

- Improves the science that drives the fire and smoke models;
- Provides valuable knowledge that advances next-generation modeling systems and operational applications;
- Provides information on effective and cost-efficient methods for measuring fuels to be entered in fire spread, fuel consumption, and fire emissions models;
- Improves operational fire and smoke models to more accurately predict wildland fire emissions, plume dynamics, and effects on air quality; and
- Improves decision support for operational fire and smoke management.

The remaining report will summarize the research and data collected for the 1) Western Wildfire campaign and the 2) Southwest campaign. Progress and preparation for the Southeast campaign at Fort Stewart, Georgia will also be presented.

4. FASMEE Western Wildfire Campaign

4.1 Background

FASMEE initiated the Western Wildfire Campaign by meeting with WE-CAN, BB-FLUX and FIREX-AQ leads and discussing the importance of fuels and source characterization to associate with emission and chemistry data collected from western wildfire plumes in 2018 and 2019. Our approach was three-pronged: 1) compile LiDAR data to map fuels and use that map as one criteria for selecting wildfires to sample during the airborne campaign; 2) collect fuels data for selected wildfires; 3) and model fuels for source characterization of wildfire sites sampled with aircraft using the Fuel and Fire Tools (FFT) software program (https://depts.washington.edu/fft/).

4.2 Methods

Source characterization of fuels was the main objective for the Western Wildfire Campaign (WWC) of FASMEE Phase 2. This included fuel measurements on the ground, and pre-fire and post-fire airborne lidar collections at five western wildfires in 2018 in support of the BB-FLUX and WE-CAN campaigns funded by NSF, and three western wildfires in 2019 in support of FIREX-AQ funded by NOAA/NASA (Fig. 3). Aboveground biomass and five fuel attributes were mapped across the entire United States following the Random Forest approach developed by Mauro et al. (2021). Relationships between lidar and climate predictors, response variables and uncertainty was modeled and mapped using a power law of the predicted response.

We developed a geodatabase of existing lidar coverage across the western US, which proved critical in support of airborne emissions measurements by the BB-FLUX, WE-CAN, and FIREX-AQ emissions measurements campaigns. We continue to update this geodatabase as more lidar is collected toward the USGS goal of national lidar coverage (perhaps as soon as 2023) and our own strategic goal of west-wide maps of fuel attributes needed by forest, fuel, and fire managers.

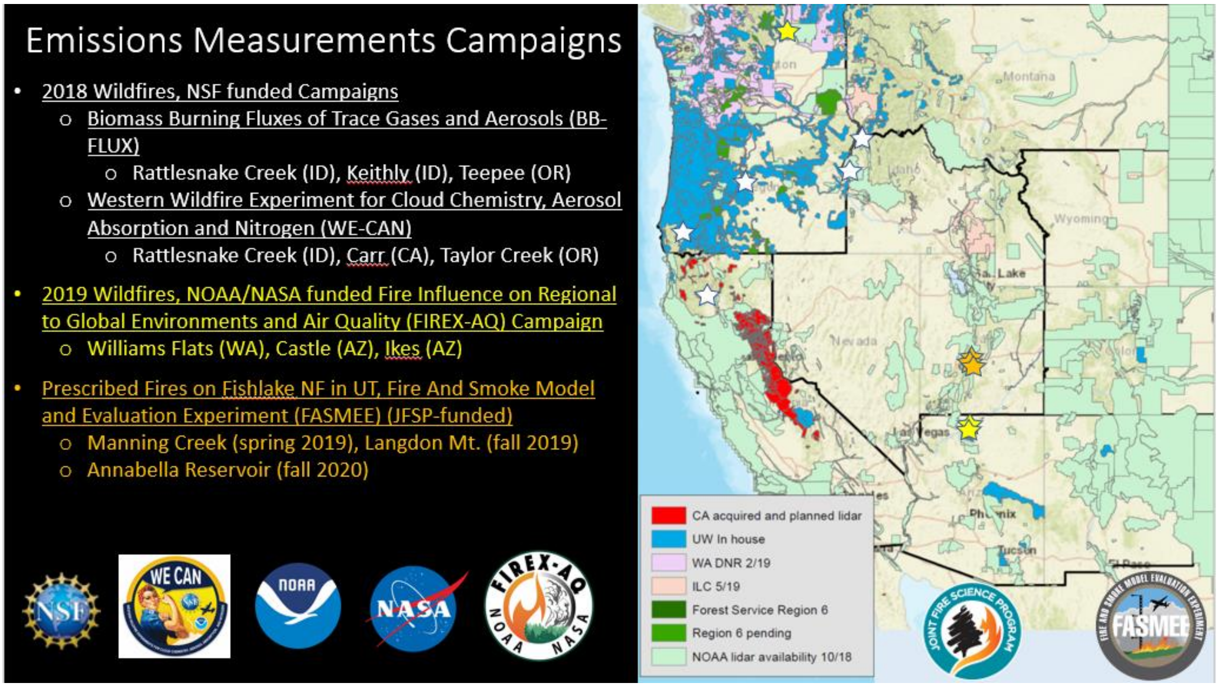


Figure 3. List and locations of wildfires (n=8) selected for the FASMEE WWC and the prescribed crown fires (n=3) for the FASMEE SW Campaign, plotted on top a map of US West lidar coverage.

Field plot data collected at about the same time as the lidar can be related through empirical models to map fuel loads (Hudak et al. 2016). We collected field data soon after the Keithly and Tepee wildfires in the fall of 2018. In summer 2019 (when post-fire lidar could be flown), we characterized the 3 other 2018 fires (Carr, Taylor Creek, Rattlesnake Creek), and then the 2019 Williams Flats fire soon after it was extinguished. Nominally at each fire, at least 20 field plots were characterized in unburned and burned conditions across low, moderate, and high burn severities and within the area delimited by pre- and post-fire lidar coverage. Stratified random sampling was limited to major Existing Vegetation Types (>10% of the area to be sampled), which served as strata to be sampled at a random location within a consistent burn severity condition. Destructive samples of shrub, herbaceous (grasses and forbs), 10-hr, 1-hr, and litter were collected within 0.5 m^2 clip plots, bagged, oven-dried, and weighed. A modified Brown's line intercept inventory method using 15 m length transects (Brown1974) was used to tally 100-hr and 1000-hr fuels. The litter and duff depths were measured at 4 systematic locations per transect. Shrub cover and height were measured at 0.5m intervals along these transects. Tree status, species, and diameter at breast height (dbh) were tallied within 8m fixed radius plots, and saplings (<10 cm dbh) within 5.6m radius subplots. Trees were measured for height, crown base height, live crown height, and percent green, scorched, or charred crown. Plot centers were monumented and geolocated to ~0.5m precision by averaging >200 logged positions after differential correction. All field data have been collated and quality assured/controlled. Plot data are being related to post-fire lidar data to fit predictive fuel models where we will apply to the pre-fire lidar to estimate consumption.

4.3 Results

4.3.1 2018 Keithly (ID) and Tepee (OR) Fires

BB-FLUX arranged for NEON (National Ecological Observatory Network) to collect lidar and hyperspectral imagery soon after the Keithly and Tepee Fires, at no cost to us (Fig. 4). The Keithly Fire burned through sparse grass fuels with some sagebrush.

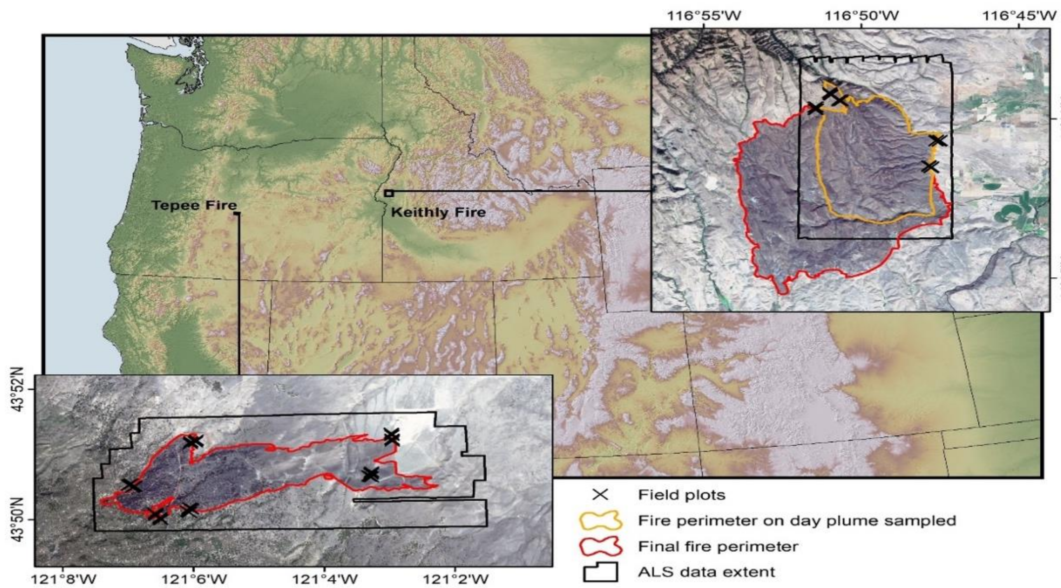


Figure 4. Location of Tepee and Keithly wildfires, with field plot locations, post-fire ALS coverage extent, and fire perimeters. The fire perimeter on the day of smoke plume sampling is shown at the Keithly wildfire. The ending fire perimeter for the Tepee wildfire is shown since the smoke plume from the entire fire was sampled.

The Tepee Fire spanned an ecotone between sagebrush and forest, where the surface vegetation composed of primarily sagebrush and some grass was consistent between non-forested and forested plots. The forested plots had the added needlecast and woody components below an open canopy of ponderosa pine.

We fit a Random Forests regression model to predict the total fuel load measured on the ground from post-fire lidar metrics (Fig. 5), applied the model to the gridded lidar metrics (Fig. 6), and differenced the resulting pre- and post-fire fuel loading maps to estimate consumption (Fig. 7). We also summarized fuel load and consumption estimates derived from FCCS maps and the CONSUME model within the same areas for comparison. We found that the lidar-derived estimates of fuel load and consumption were considerably lower than those estimated from the LANDFIRE maps of FCCS and CONSUME (Fig. 8). We believe that the fuel loads at these wildfires were lower than the mean fuel condition represented in categorical FCCS maps nationally, especially the sparse grass fuels

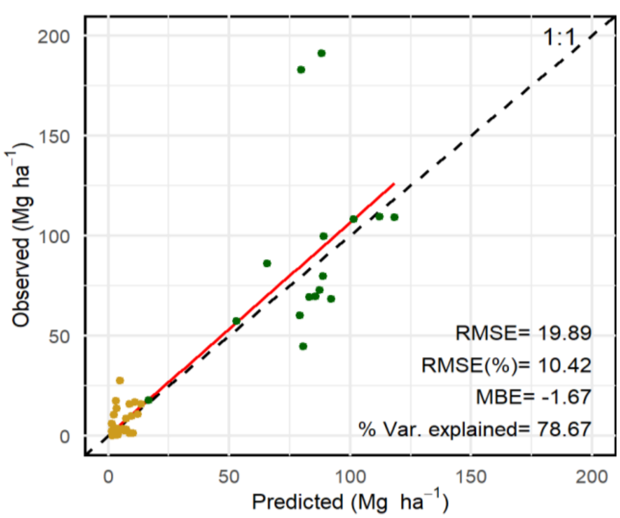


Figure 5. Performance statistics for Random Forest model of lidar metrics and field data, with 1:1 (dashed) and best-fit (solid) lines. Colors distinguish forested plots (green) and rangeland (yellow).

at the Keithly Fire. Consumption estimates from lidar data was in closer agreement with those modeled with CONSUME, especially for the Tepee Fire.

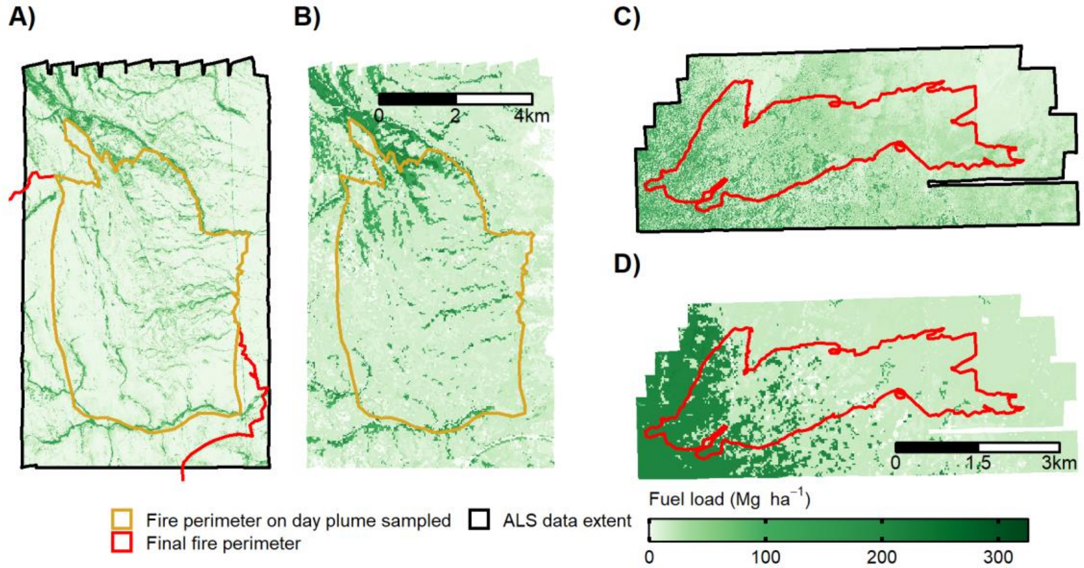


Figure 6. Pre-fire fuel load for the Keithly Fire (A & B) and the Tepee Fire (C & D) derived from ALS data (A & C) and from FCCS data (B & D).

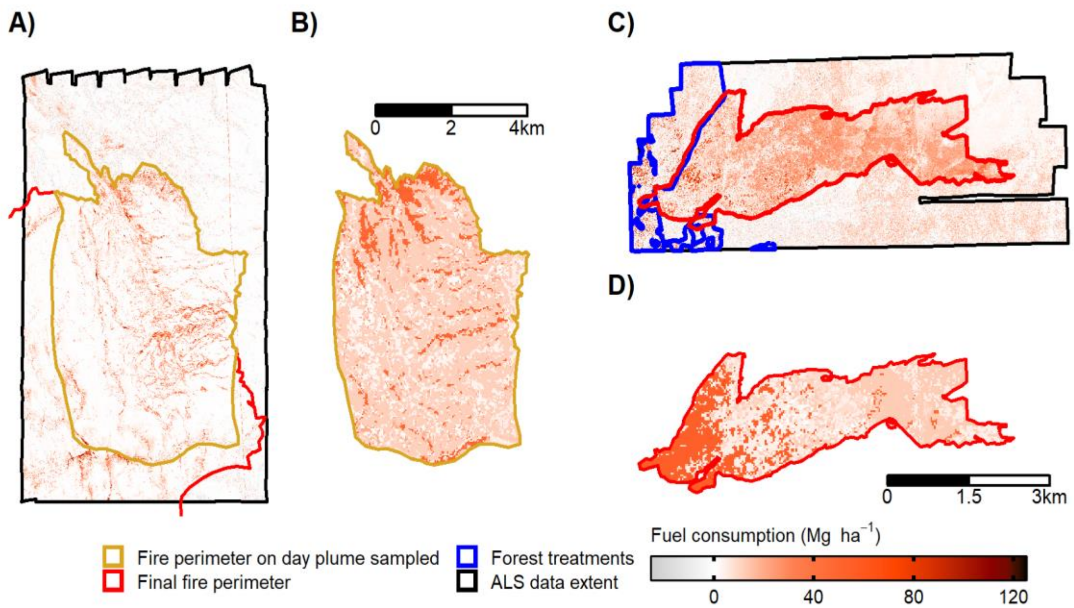


Figure 7. Fuel consumption for Keithly (A & B) and Tepee Fires (C & D) derived from ALS data (A & C) and FCCS-FFT outputs (B & D). Tepee Fire forest treatments occurred between pre- and post-fire ALS acquisitions and prior to the Tepee Fire, falsely indicating consumption outside the perimeter (C).

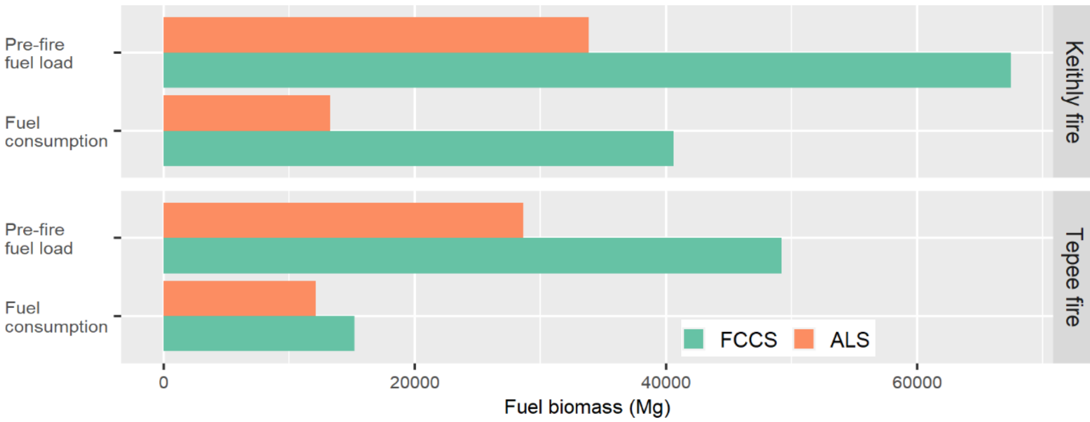


Figure 8. Estimated pre-fire fuel load and fuel consumption for the Keithly Fire on 26 July 2018 and the Tepee Fire on 8 September 2018, the dates when the smoke plumes were sampled by an aircraft.

4.3.2 2018 Rattlesnake Creek (ID) Fire.

The 2018 Rattlesnake Creek Fire, the first western wildfire sampled by both BB-FLUX and WE-CAN, spanned the northern edge of Adams County, Idaho which was slated for airborne lidar collection in 2019 as part of the USGS 3D Elevation Program (3DEP). FS Region 4 paid the lidar vendor to upgrade the lidar pulse density from Quality Level 2 (QL2, suitable for rangelands) to QL1 (more suitable for forests), and to include the portion of the wildfire north of the county line, where we had decent road access for field sampling, in order to benefit our project and at no added cost to us. The lidar was not flown until late fall 2019, but early snowfall at high elevation necessitated reacquiring portions in spring 2020 after snowmelt. Two years later, we are still waiting for the lidar data, while the deliverables navigate the USGS 3DEP QA/QC protocols for 1m resolution digital elevation data.

4.3.3 2018 Carr (CA) and Taylor Creek (OR) Fires.

We contracted NASA's G-LiHT system for \$30K to collect lidar and hyperspectral imagery a year after the Carr and Taylor Creek Fires along 100m-wide strip transects separated by 1 km. This strategy allowed broader sampling across a wider extent of these large wildfires with limited funds. Two years later, we are still waiting for G-LiHT data delivery. Our analytical strategy is to predict burned and unburned fuels along the G-LiHT transects (where we positioned the field plots), and then fit partial least squares regression models to fill in the wide gaps between the narrow G-LiHT transects, using high-resolution, WorldView-3 multispectral (1.3 m) and panchromatic (0.5 m) satellite imagery collected on 07/02/2019 (Carr) and 07/03/2019 (Taylor Creek), which we have geometrically and radiometrically rectified.

4.3.4 2019 Williams Flats (WA) Fire.

The 2019 Williams Flats Fire in eastern WA produced the smoke plumes most sampled by the FIREX-AQ DC-8 aircraft on 4 separate days, making it the primary wildfire of interest to FIREX-AQ. For fuels characterization, Hudak piggybacked a post-fire lidar collection on to a large, multi-partner contract with a lidar vendor that was just finishing collections in neighboring Idaho, in late September. Most of the fire (14,435 ha) was flown at a low cost of \$22K because the plane was already nearby in Coeur d'Alene. Meanwhile, the high-altitude ER-2 aircraft collecting active fire hyperspectral AVIRIS imagery for FIREX-AQ flew three transects over broad swaths of the actively burning area, avoiding wherever the plume happened to be for an unobscured view, yet effectively covering the range of burned/unburned conditions and including most of our field plots. Full multispectral image coverage of the burn area was obtained from 10m resolution Sentinel imagery.

Through an unfunded collaboration with Dr. Dar Roberts and PhD student Claire Saiki at the University of California, Santa Barbara, partial least squares (PLS) regression estimates are being used to extrapolate estimates of physical fuel attributes to the entire fire, after fitting models to associate the field plot measures with lidar and AVIRIS (Fig. 9).

Per our WWC approach, we fit models between field plot measurements of fuels and post-fire lidar metrics, applied the models to generate pre- and post-fire maps of fuel loads, and differenced the maps to estimate consumption. Vegetation ranged from non-forested sagebrush/grass and dry ponderosa pine forest like at the Tepee Fire, to dry mixed conifer forest at higher elevations. Since lidar provides vertical resolution, we fit separate models for canopy fuels and surface fuels (Fig. 10). Although the models were noisy, the best fit lines show little evidence of bias or disproportionality in the predictions (i.e., good agreement with the 1:1 line). Consequently, mapped estimates of fuel load and consumption (Fig. 11) should be reliable upon in aggregation to estimate total emissions from within the burn perimeter. Indeed, the landscape patterns in estimated consumption are similar to landscape patterns in delta Normalized Burn Ratio (dNBR) considered indicative of burn severity and derived from independent data (Figure 9). Finally, the high-altitude ER-2 aircraft deployed for FIREX-AQ collected active fire thermal infrared imagery over both fires, from which cooperators at the NASA Jet Propulsion Laboratory (JPL) can derive consumption estimates; these would provide independent validation of our own consumption estimates derived by differencing the pre- and post-fire lidar collections.

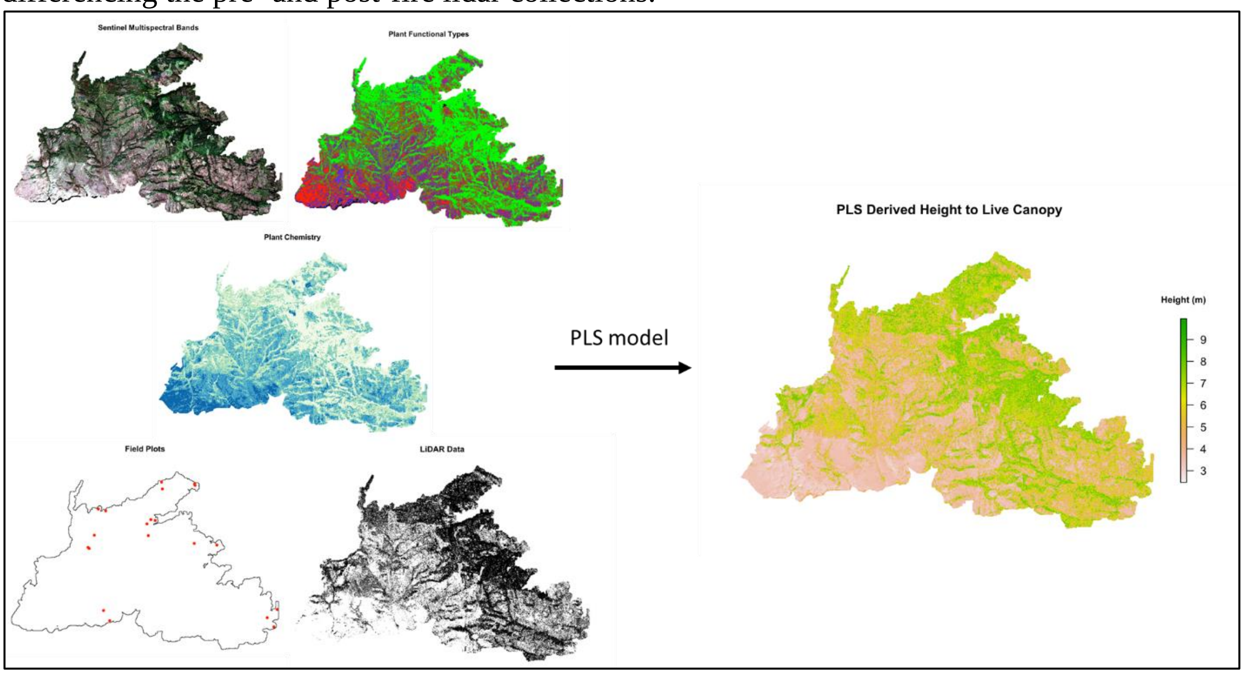


Figure 9. Physical fuel properties derived from field plots and AVIRIS hyperspectral image swaths (not shown), extrapolated to the entire Williams Flats Fire from Sentinel multispectral imagery and lidar using partial least squares regression (PLS).

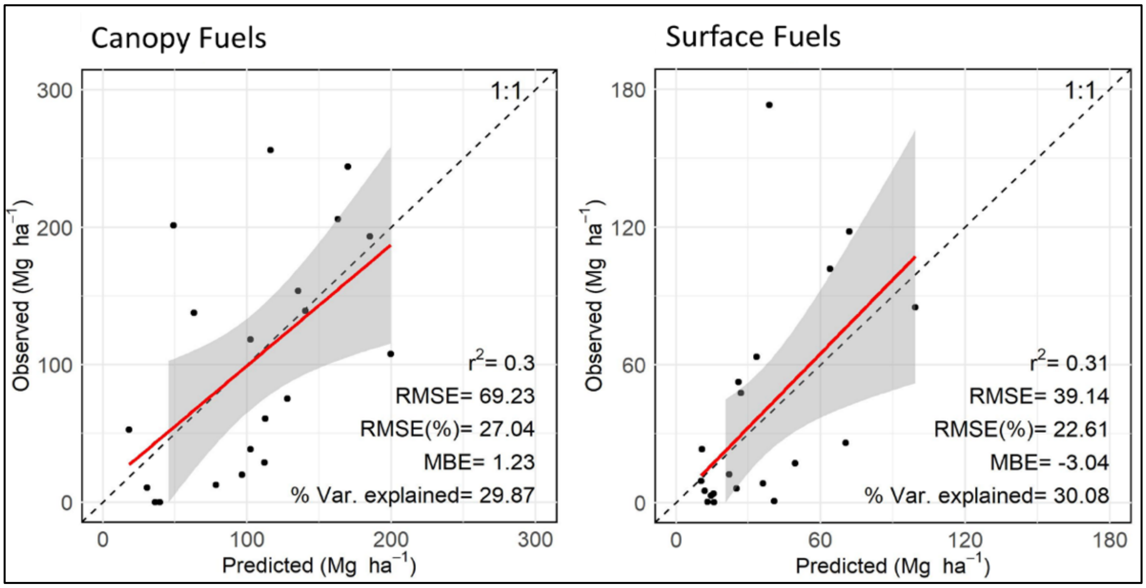
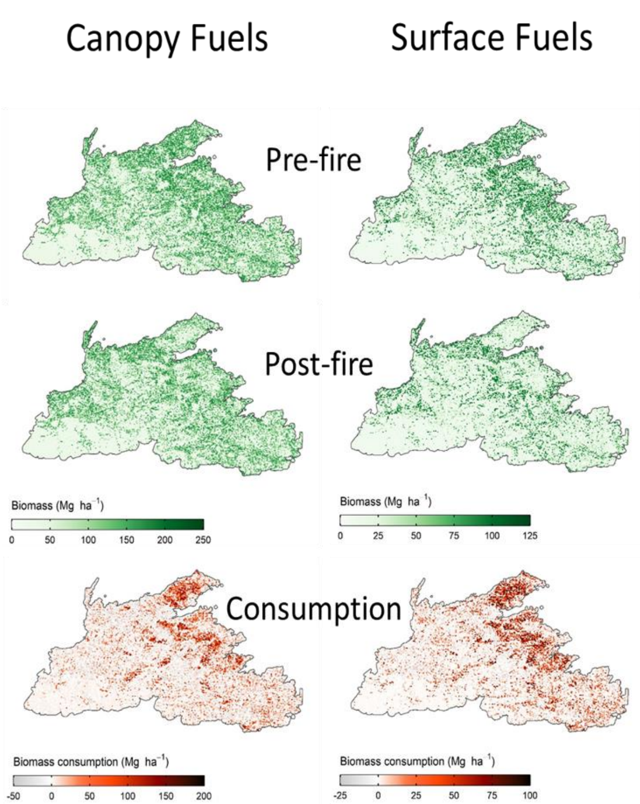


Figure 10. Random Forest models predicting canopy and surface fuels at the Williams Flats Fire.



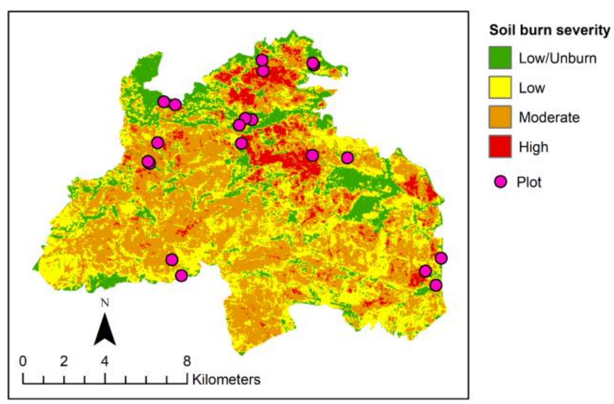


Figure 11. Canopy and surface fuel loads predicted from lidar pre- and post-fire across the Williams Flats Fire, then differenced to estimate consumption. Note similarity between fuel consumption patterns and classified delta Normalized Burn Ratio (dNBR) indicative of soil burn severity. Note that the lidar footprint on the left covers most, but not all, of the final fire perimeter as depicted in the classified dNBR map at right.

4.3.5 2019 Castle and Ikes (AZ) Fires.

The opportunity to fly post-fire lidar and color orthoimagery over the 2019 Castle and Ikes fires in the Kaibab NF came in 2020, in the same contract as funded post-fire lidar collection following the 2019 Manning Creek and Langdon Mountain fires in the Fishlake NF as part of the FASMEE SW campaign, for a combined $45K (Fig. 12). However, COVID-19 travel restrictions in 2020 prevented fieldwork. Fortunately, the Kaibab National Forest and Grand Canyon National Park have collected fuel measurements for 10 years in accurately geolocated field plots as part of their cooperative fuels and fire management. They shared these field plot data with us which, depending on the field plot date, we are relating to 2012 or 2019 *pre-fire* lidar collections to fit predictive fuel models, which we will also apply to the *post-fire* lidar collected a year after the Castle and Ikes fires, such that consumption can be estimated. In addition, the availability of 1984-2019 fire history records affords us the opportunity to include time since fire as a predictor in fuel models. Finally, the high-altitude ER-2 aircraft deployed for FIREX-AQ collected active fire thermal infrared and hyperspectral imagery over both fires, from which consumption estimates could be derived by cooperators at NASA JPL, which would provide an independent consumption estimate to compare to ours derived from pre- and post-fire lidar collections.

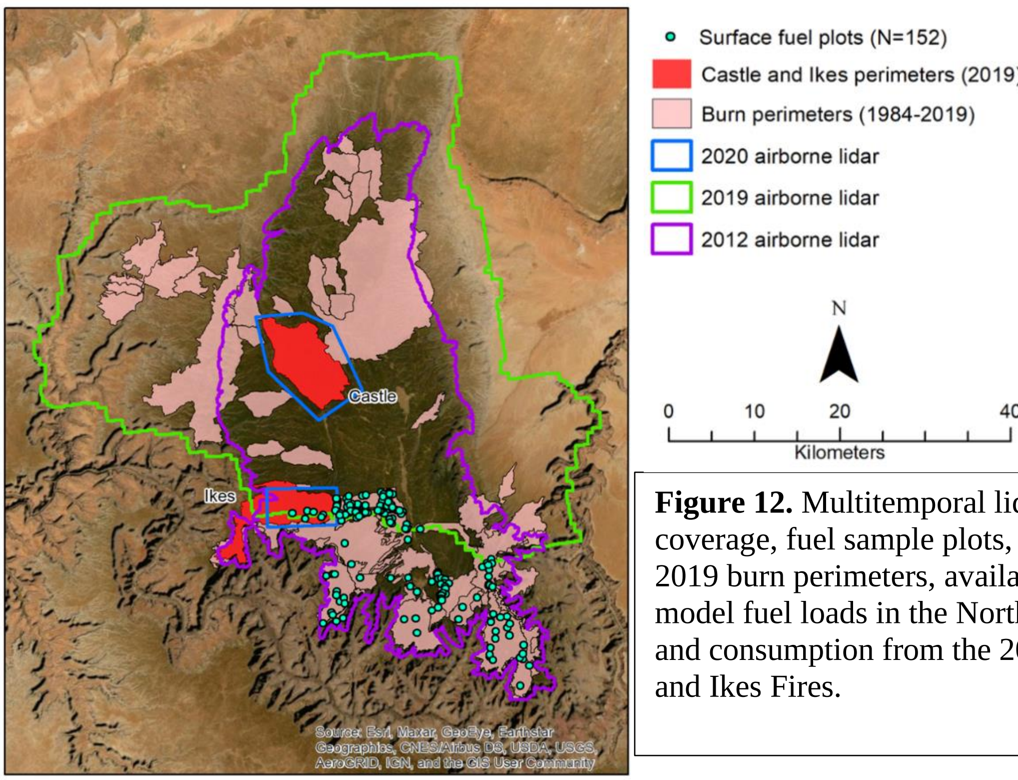


Figure 12. Multitemporal lidar coverage, fuel sample plots, and 1984-2019 burn perimeters, available to model fuel loads in the North Kaibab, and consumption from the 2019 Castle and Ikes Fires.

4.3.6 2019-202 Manning, Langdon, and Annabella Reservoir (UT) Rx Fires.

These three prescribed crown fires of the FASMEE SW Campaign were characterized with post-fire lidar and color orthoimagery one year after the burns (Fig. 13). The 2020 collection was included in the $45K contract that also acquired the Castle and Ikes Fires in AZ (described above). The 2021 collection of the one-year post-fire Annabella Reservoir scene was accomplished through a $25K sole-source contract with the same lidar vendor to ensure consistent data for analyses.

During the 2019 FIREX-AQ summer campaign on 21 August 2019, the high-altitude ER-2 aircraft collected hyperspectral AVIRIS imagery over a single broad swath through the Monroe Mountain District that includes all of the Manning Creek post-fire scene, most of the Langdon Mt. pre-fire scene, all of the Annabella Reservoir pre-fire scene, and all field plots associated with all three of these burns (Fig. 13). Thus, physical fuel properties have been modeled and mapped via PLS regression, just as they were at the Williams Flats Fire, as illustrated above in Figure 7. This work is being accomplished through a collaboration with Dr. Dar Roberts and PhD student Claire Saiki at UC-Santa Barbara.

Finally, to capture delayed fire effects and post-fire vegetation recovery, high-resolution (1.85m) WorldView-2 was acquired on 06/23/2019, 07/06/2019, 09/01/2019 and 07/01/2020, and 1.3m resolution WorldView-3 imagery was acquired on 07/17/2019 and 08/07/2021, The imagery captures not just the three prescribed crown fires of the FASMEE SW campaign but also other operational burns prescribed by Fishlake NF managers in the Monroe Mountain District.

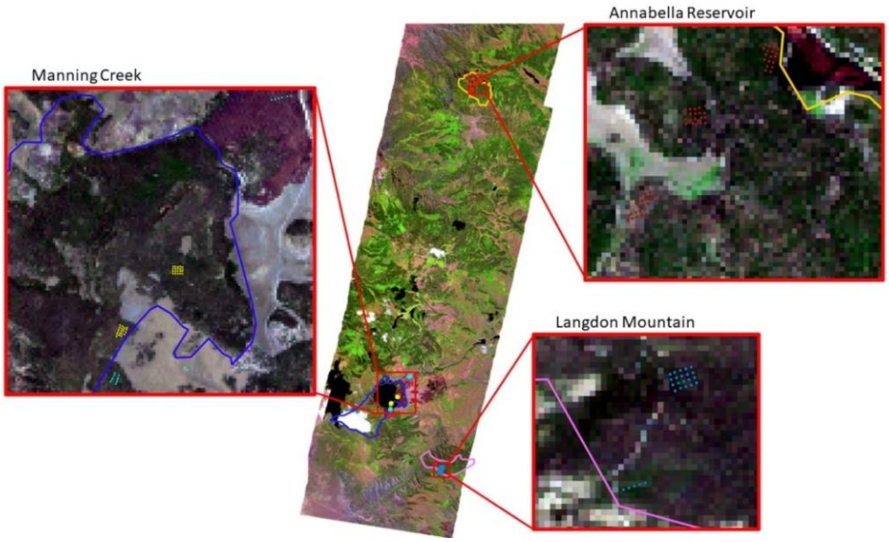


Figure 13. An ER-2 aircraft collected a hyperspectral AVIRIS image swath on 21 August 2019 over the Manning Creek (post-fire), Langdon Mt. (pre-fire) and Annabella Reservoir (pre-fire) Fires.

5. FASMEE Southwest Campaign

The southwest campaign was conducted on the Richfield Ranger District of the Fishlake National Forest in Utah. There were four stand replacement research burns including Manning Creek black line (2018), Manning Creek (2019), Langdon Mountain (2019) and Annabella Reservoir (2020). Because of Covid-19, funding and instrumentation malfunctions, not all disciplines were able to conduct research on each burn (Table 1).

Table 1. Participating FASMEE science disciplines during southwest campaign research burns.

Research Burns	Date of Burn	Area (Acres)	Research Disciplines				
			Fuels	FB&E	Plume	Smoke	Effects
Manning Creek Blackline	24-Nov-18	400	X				
Manning Creek	20-Jun-19	1100	X	X	X	X	X
Langdon Mountain	7-Nov-19	1000	X	X	X		X
Annabella Reservoir	5-Nov-20	750	X		X	X	X

5.1 Fuels

5.1.1 Background

The fuels discipline provides data that characterizes all pre- and post- fire fuel components including trees, shrubs, grasses, downed woody, liter, and duff. That is critical for the fire behavior, energy, plume dynamics, smoke and fire effects disciplines. This section describes the fuel data collected on the 3 stand replacement prescribed fires as part of the FASMEE SW campaign on the Fishlake National Forest collected by the Fire and Environmental Research Team (FERA) at the Pacific Wildland Fire Research Laboratory (PWFSL) located in Seattle, WA.

5.1.2 Methods

Fuels were measured at each burn unit to provide area-wide averages of pre- and post-fire fuel loading of surface fuels, fuel moisture, and verification data for remotely sensed overstory characteristics and burn severity (Fig. 14). Groups of plots, hereafter referred to as sites, were systematically arranged within stand boundaries of representative burnable vegetation types. In total we established 130 plots at seven sites (Table 2). Site B at Annabella Reservoir did not burn and is excluded from results. Plot centers were permanently monumented with conduit poles with steel tag plot labels. Plot centers were photographed before and after the prescribed burn from permanently marked camera locations located 16 ft from the plot center. Coordinates were collected for plot centers with a GNSS receiver with an L2 antenna (Javad Triumph-2, Javad GNSS, Inc., San Jose, CA).

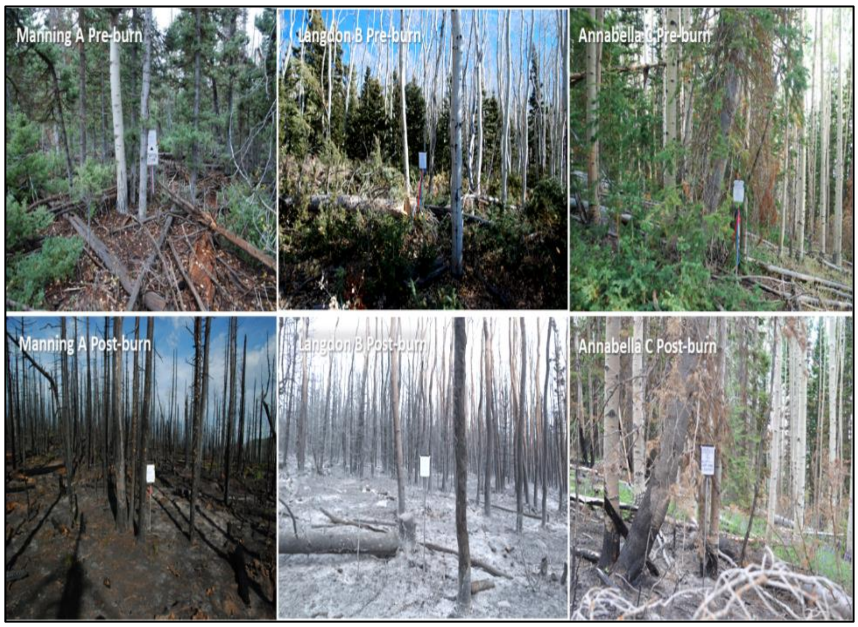


Figure 14. Pre- and post-fire photos of representative stands at three FASMEE research sites on the Fishlake National Forest.

Table 2. Research prescribed burn unit information.

Manning Creek Blackline	10/18	11/24/18	8/19	10	Mixed sub-alpine fir/quaking aspen overstory, high fuel load
Manning Creek A	6/19	6/20/19	8/19	10	Mixed sub-alpine fir/quaking aspen, high fuel load
Manning Creek B	6/19	6/20/19	8/19	10	Quaking aspen overstory/sub-alpine fir understory, high fuel load
Langdon Mountain	11/19	11/7/19	11/19	20	Quaking aspen overstory/sub-alpine fir understory, high fuel load
Annabella Reservoir A	9/19	11/5/20	7/21	20	Quaking aspen overstory/sub-alpine fir understory, high fuel load
Annabella Reservoir B	9/19	11/5/20	7/21	20	Dead Engelmann spruce overstory/subalpine fir understory, high fuel load
Annabella Reservoir C	9/19	11/5/20	7/21	20	Quaking aspen overstory/sub-alpine fir understory, high fuel load

Fuel bed categories of shrubs, grasses, woody debris, litter, and duff were measured at plots (Fig. 15). Coarse (100-hr; 1-3 in. and 1000-hr; > 3 in.) downed woody debris (DWD) loading was measured before and after burns along planar intercept transects (Brown 1974, Fig. 15). Forest floor loading was estimated by measuring pre- and post-fire litter and duff depth profiles at eight locations at each plot spaced 0.8 ft apart (Fig. 16). Pre- and post-fire loading was calculated by applying known bulk density values to the average depth (Prichard et al. 2017). Loadings for remaining surface fuel categories were measured in biomass clip plots. A set of pre- and post-fire nested sub-plots (0.8 ft^2 and 3.3 ft^2) were established at each plot to measure biomass of fine (1-hr; 0-0.25 in. and 10-hr; 0.25-1 in.) DWD and standing vegetation (Fig. 3). Within each 0.8^2-ft sub-plot, we removed aboveground portions of herbs and fine DWD. Aboveground biomass of trees less than 4.5 ft tall, layered branches (i.e., subalpine fir branches that had rooted into the ground), and shrubs were removed from the 3.3-ft^2 clip plots. Pre- and post-fire biomass was calculated from oven-dry weights for each category.

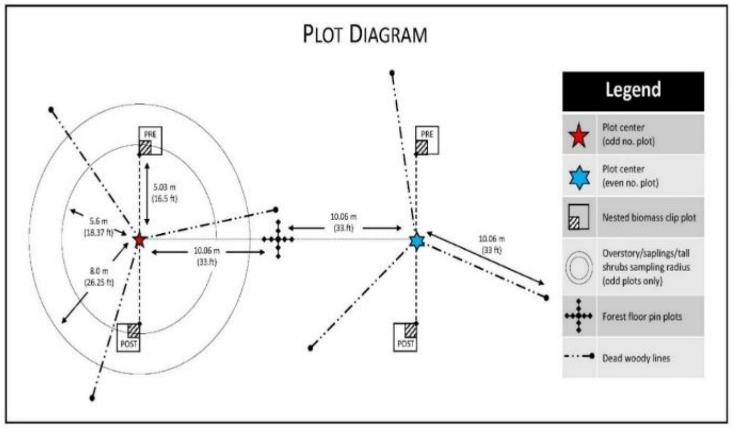


Figure 15. Plot diagram with location and orientation of plot-level measurements.

Overstory (DBH > 4.7 in.) and sapling (DBH ≤ 4.7 in. and height > 4.5 ft) surveys were conducted at odd-numbered plots. Overstory tree characteristics were censused in 26.2-ft fixed radius plots. Saplings were tallied in 18.4-ft fixed radius plots. White ash fraction was also estimated in post-fire clip plots. These variables provide verification datasets for Andy Hudak's research to test the efficacy of remote sensing products to measure overstory characteristics and burn severity.

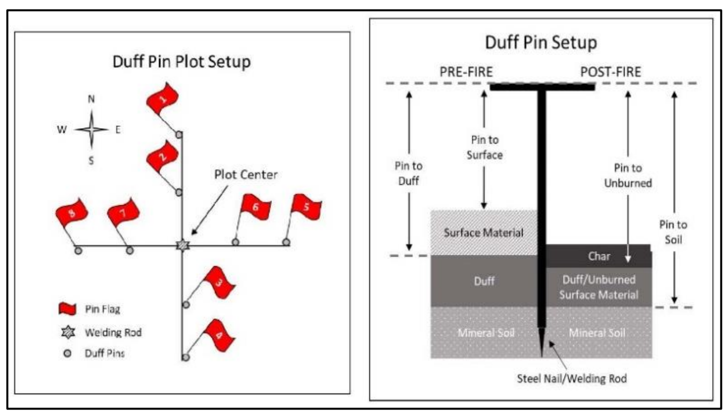


Figure 16. Left: Forest floor plot set-up and pin orientation. Right: Duff pin measurement.

We collected fuel moisture samples from each burn unit except Blackline 2018. At least 10 samples were collected of 1-hr, 10-hr, 100-hr, and 1000-hr DWD, live conifer foliage, litter, and duff fuel categories. Fine fuel moisture samples were sampled within 1 hour of ignition or during the burn and coarse fuel moisture samples were sampled 1-2 days prior. A single wire was secured around 1000-hr fuels that were sampled to measure diameter reduction. Moisture samples were placed in re-sealable plastic bags. Wet moisture weight was recorded the day of collection. Samples were oven-dried for 48-72 hours at 158° F to obtain dry weights.

5.1.3 Results

Prescribed burns reduced surface fuel loading by an average of 57 percent (39.7 tons per acre) across sites (Fig. 17). Total pre-fire loading was between 41.3 and 92.4 tons per acre. Aspen-dominated sites had, on average, 62 percent lower loading than sites where overstory was mixed fir-aspen or subalpine fir (Table 2). Consumption was greater than 50 percent of the surface fuel load at all sites except those located in the Annabella Reservoir burn unit. Lower consumption at this unit was likely due to snowfall prior to the burn. On average, 39 percent of surface fuels were consumed at aspen-dominated sites versus 66 percent at mixed aspen-fir and fir sites. The lower consumption at aspen sites could be because aspen is less flammable than fir and thus aspen stands burned at lower intensities reducing fuel consumption. However, this trend does not hold up when sites are paired within burn units. While the subalpine fir site at Manning Creek had higher consumption (69 percent) than the aspen site (43 percent) in the same unit, consumption at the mixed aspen-fir site (25 percent) at Annabella Reservoir was lower than the aspen site (36 percent). Lower than expected percent consumption at the mixed aspen-fir stand at Annabella Reservoir was likely due to snow cover and higher fine fuel moisture because shade from subalpine fir prevented snowmelt whereas the lack of foliage in the canopy at the aspen site permitted increased solar radiation and wind flow that melted and evaporated much of the snow cover prior to the burn.

The majority of surface fuel loading across all sites was concentrated in coarse fuels (Table 3). These fuels are less important to fire behavior but contribute substantially to smoke emissions. Coarse fuels include the duff layer of the forest floor and downed woody debris greater than 1 inch in diameter (i.e., 100-hr and 1000-hr DWD). Fraction of total surface fuel loading for coarse fuels was 87-95 percent across all sites and was evenly split between duff (49 percent) and 1000-hr DWD (38 percent). Fine fuel loading was 3.6-9.4 tons per acre and concentrated in the low-growing conifers (20-60 percent) and litter (18-52 percent). Loading among fuel categories was generally consistent among all sites except Annabella C.

Fuel consumption was consistently high for fine fuel categories at the Blackline 2018, Manning Creek, and Langdon Mountain sites compared with the Annabella Reservoir sites (Table 3). At the former sites where the ground was dry, fine fuel consumption was 87-97 percent, while at the Annabella Reservoir sites it was 49-50 percent. Most of this difference was concentrated in dead fuels on the ground (i.e., litter and fine DWD) which would have been covered in snow across much of the Annabella Reservoir sites. Consumption of coarse fuels varied among sites but did not display the same trend as fine fuels, because coarse fuel consumption depends on seasonal weather patterns.

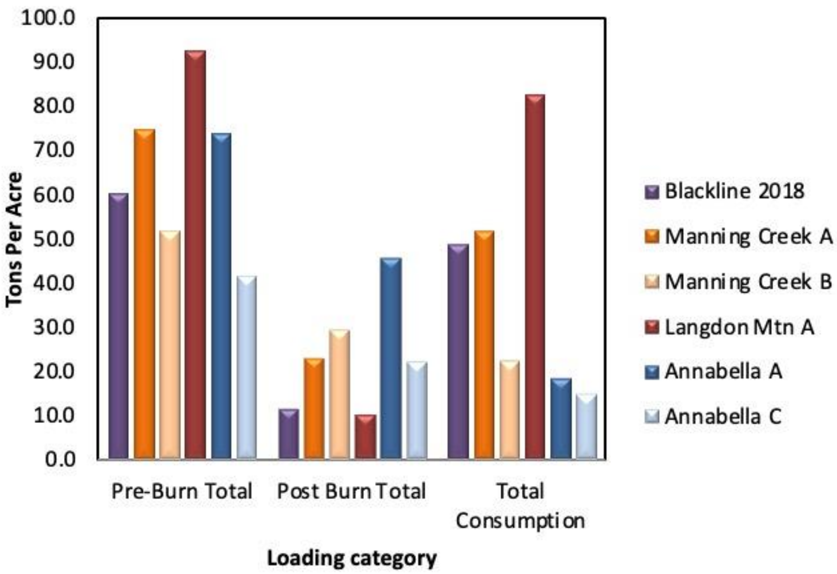


Figure 17. Pre- and post-fire loading, and total consumption (pre-fire minus post-fire) of surface fuels at each of the burned sites established on the Fishlake National Forest for FASMEE research between fall 2018 and fall 2020.

Table 3: Pre-fire loading (tons per acre) and percent consumption (in parentheses) by fuel category for each site.

Site[1]	Forest Floor		Downed Woody Debris				Standing Vegetation (< 4.5 feet tall)		
	Litter	Duff	1-hr	10-hr	100-hr	1000-hr	Conifer[2]	Hardwood[3]	Herbs[4]
BL	1.72 (100%)	29.05 (72%)	0.21 (98%)	0.67 (98%)	2.24 (65%)	23.75 (93%)	2.41 (94%)	0.00 (--)	0.00 (--)
MC A	0.98 (99%)	30.96 (55%)	0.19 (100%)	0.51 (92%)	4.07 (70%)	34.92 (79%)	2.88 (87%)	0.04 (100%)	0.00 (--)
MC B	1.15 (99%)	34.95 (36%)	0.09 (76%)	0.51 (92%)	4.01 (28%)	9.11 (57%)	1.82 (78%)	0.03 (100%)	0.00 (--)
LM	2.57 (100%)	46.65 (99%)	0.19 (100%)	0.52 (100%)	3.42 (83%)	37.34 (76%)	1.63 (73%)	0.01 (100%)	0.00 (--)
AR A	1.72 (49%)	33.36 (44%)	1.65 (62%)	4.16 (40%)	2.40 (32%)	28.59 (29%)	1.85 (61%)	0.01 (81%)	0.00 (--)
AR C	1.62 (46%)	17.30 (36%)	0.62 (79%)	1.50 (9%)	3.53 (41%)	15.47 (60%)	1.24 (89%)	0.01 (55%)	0.03 (0%)

[1]Site codes: BL = Blackline 2018, MC A = Manning Creek A, MC B = Manning Creek B, LM = Langdon Mountain, AR A = Annabella Reservoir A, AR C = Annabella Reservoir C

[2]Conifer category includes seedlings, saplings less than 4.5 feet tall, common juniper, and sub-alpine fir branches that have rooted into the ground.

[3]Hardwood category includes deciduous shrubs, and aspen seedlings and saplings less than 4.5 feet tall.

[4]Herb category includes grasses and forbs.

Average fuel moisture across sites reflected expected patterns with highest values in living vegetation and coarse dead fuels and lowest percentages in dead fine fuels (Fig. 18). Fuel moisture values for each site broadly correspond with patterns of consumption. The highest dead fine fuel moisture values were measured at Annabella Reservoir where consumption was lower than other sites. Live fine fuel moisture (conifer foliage) was consistent across all sites. This is expected as living trees and shrubs with evergreen foliage maintain consistent foliar moisture, except during dry periods. This also reflects similar percent consumption values across all sites despite the higher dead fine fuel moisture and snow cover at the Annabella Reservoir sites, Coarse fuel moisture values at the Annabella sites were similar to other sites showing that these values are an artifact of seasonal weather patterns.

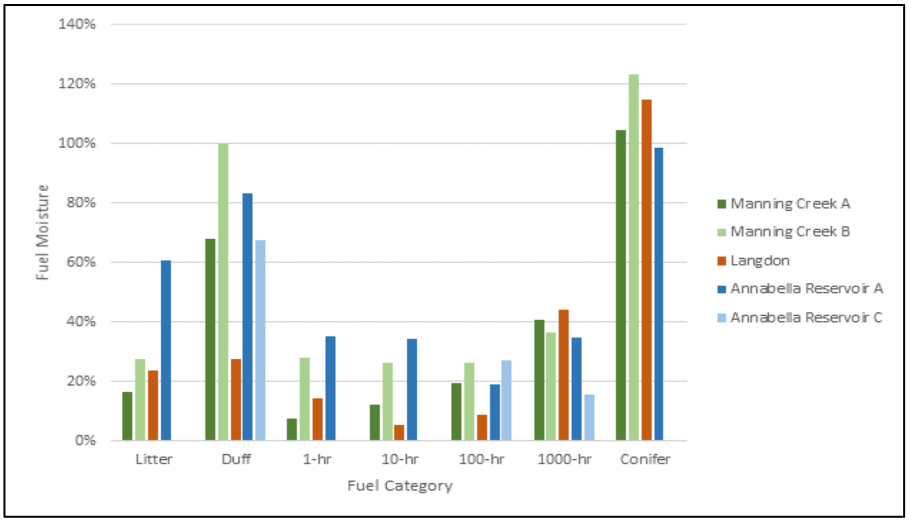


Figure 18. Percent fuel moisture for fuel categories sampled at site established on the Fishlake National Forest for FASMEE research between fall 2019 and fall 2020.

5.1.4 Conclusions

Surface fuel and consumption plots provided estimates of fuel loading and consumption for common vegetation types at four prescribed burn units that were ignited between 2018 and 2020. Fuel moisture samples and consumption data for individual coarse DWD were collected in 2019 and 2020. Pre-fire loading estimates of surface fuels were between 40 and 100 tons per acre and most biomass was concentrated in the 1000-hr timelag DWD and duff. While these fuels have less of a contribution to fire spread and intensity relative to fine fuels, the high biomass can be a major contributor to smoke emissions if fuels are consumed. Fine fuel loading was primarily distributed between litter and layered conifer branches which spread from the base of sub-alpine fir trees. Given low loading of other fine fuels, these fuel categories were likely the primary carrying fuel for most of the unit when during burning operations. While there are not enough data points for analysis ($n = 6$), dead fine fuel moisture appears to be inversely correlated with consumption. Coarse DWD fuel moisture is not correlated with consumption.

5.2 Fire Behavior and Energy

5.2.1 Background

FASMEE requires a strong in-situ and remote sensing fire component to measure heat release and spread. These data are needed to evaluate and initialize newly advanced coupled-atmospheric models that provide spatially explicit heat source information required to initialize both fire behavior and plume models. There is still much that is not understood about energy transport in fires burning natural fuels. Some current questions are (1) how the relative contribution of radiant and convective heating varies with vegetation and burning environment; (2) what are the temporal characteristics of each; (3) does the contribution of each vary through the burning period; (4) how does each contribute to ignition and fire spread; and (5) does fire energy release relate to emissions production and if so in what way?

5.2.2 Methods

Fire behavior packages (FBP) were positioned at the Manning Creek and Langdon Mountain research burns during the FASMEE SW campaign Fig. 19). FBPs provided temperature, air flow and energy sensors for quantifying energy and mass transport in wildland fires. In addition, a video camera provided visual imagery of the fire front at it passed the sensor.

The Fire Behavior and Energy discipline also is coordinating the development of an airborne sensor for measuring heat source on wildland fires. The discipline is also assessing available fire energy data sets collected during the NASA and NOAA FIREX-AQ campaign.

Figure 19. Fire behavior package following fire front at the Manning Creek prescribed fire.

5.2.3 Results

The data collected from the two burns where the FBP were deployed is currently being analyzed. Several videos from FBPs have been uploaded onto the FASMEE website and have been used in over 50 training classes since 2019. Two publications are in progress with data being uploaded into a repository following analysis.

The Fireball heat source airborne sensor has been developed. Although it was not deployed on the Annabella stand replacement fire in 2020 because of delivery problems, it is ready and will be deployed at the southeast campaign at Fort Stewart burn in 2022. The project encouraged the USFS and NASA to complete their collaborative upgrades to the Autonomous Modular Sensor (AMS) that was built by NASA Ames Research Center and currently resides with the US Forest Service. Active fire energy from the MASTER and ER-2 were collected on a subset of wildfires sampled during the project including the Williams Flat wildfire (Fig. 20).

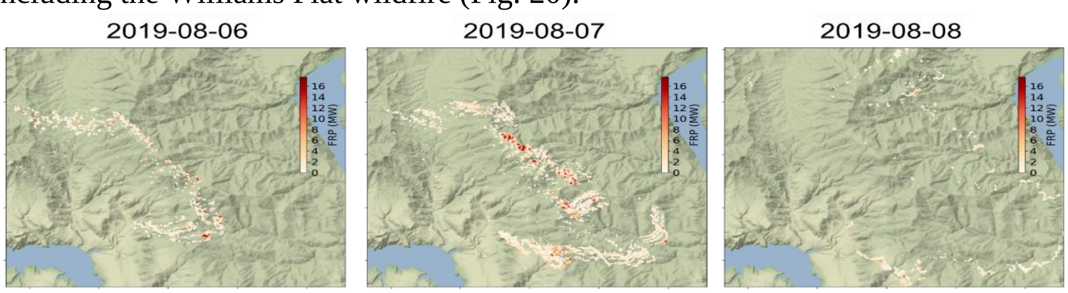


Figure 20. Mapped fire radiative power (FRP) derived from NASA airborne infrared data from the eMAS sensor collected three days over the 2019 Williams Flats fire at 2.38 µm wavelength.

5.2.4 Conclusions

The fire behavior and energy discipline made substantial strides in developing protocols to collect both in-situ and airborne fire behavior and energy data during both wildfires and prescribed fires. Energy data collected from new NASA sensor systems, advanced FBP, and recently developed airborne Fireball system will provide the information needs for advancing fire and smoke models. The scientists are currently collaborating with FIREX-AQ and other FASMEE measurement teams on additional multi-disciplinary analyses, presentations, and publications that are focused on assessing the value and limitation of this type of data for fire model advancement.

5.3 Plume Dynamics and Meteorology

5.3.1 Background

A critical research discipline from the original FASMEE study plan for advancing smoke models is plume dynamics and meteorology. This discipline provides the connection between fire behavior, energy generated and moisture emissions to vertical and horizontal atmospheric circulation and far-field smoke dispersion. Understanding the vertical distribution of the emissions is critical to the advancement of operational fire and smoke models if we are to improve the accuracy of predicting wildland fire emissions and the resulting consequences on air quality.

5.3.2 Methods

During the summers of 2018 and 2019, the San Jose State University mobile profiling system was deployed to several wildfire incidents as part of the FASMEE western wildfire campaign, including the Carr, Donnel, Kincaide, South Monroe, and Briceburg wildfires. The profiling system was also deployed to three FASMEE southwest campaign stand replacement fires including Manning Creek, Langdon Mountain, and Annabella Reservoir. The system includes a scanning Doppler lidar, microwave profiler, radiosonde system, automated weather stations, and a newly acquired Polarimetric Doppler radar (Fig. 21).

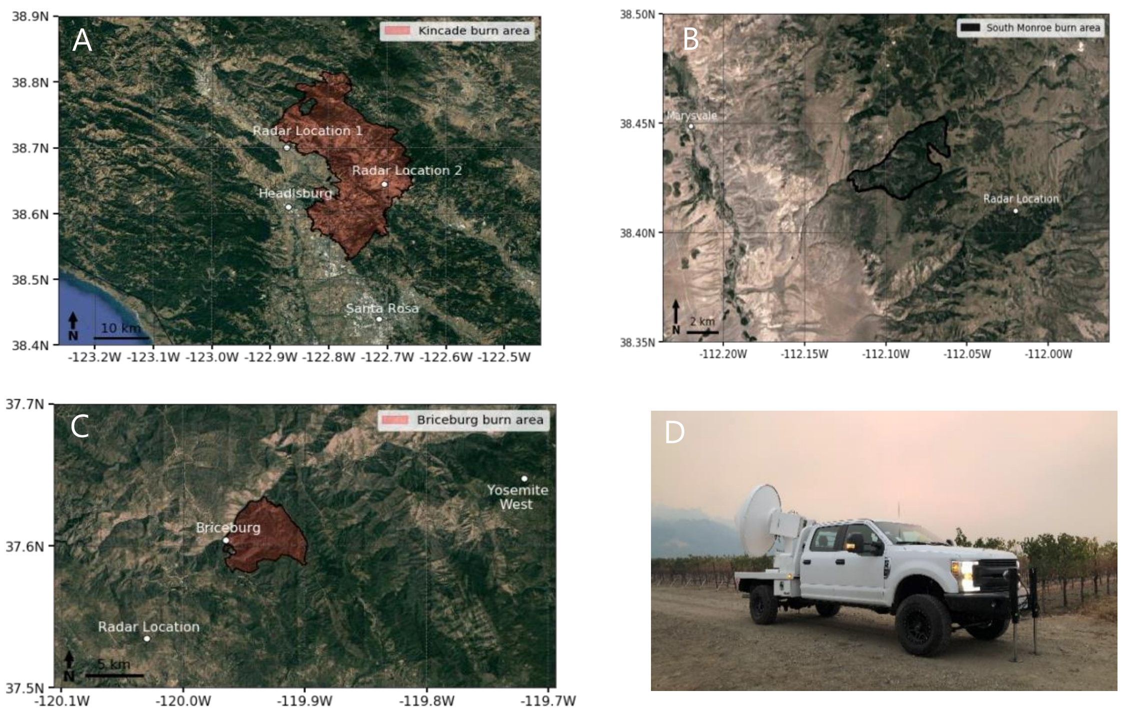


Figure 21. Maps of deployments to the (A) Kincade, (B) South Monroe, and (C) Briceburg fires, and the location of the radar site. (D) is a photo of the radar unit during the first deployment, 23 Oct 2019.

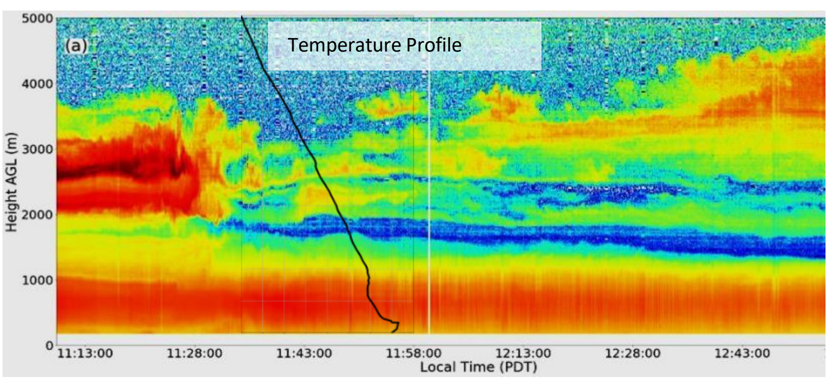
The Halo Photonics scanning Doppler lidar records attenuated backscatter coefficient and 2) the Doppler velocity. The backscatter coefficient is sensitive to micrometer-sized aerosols, including forest fire smoke. The doppler velocity data were used to investigate aspects of airflow in and around the convective plume and within the ambient convective boundary layer.

The Ka-band Scanning Polarimetric Radar (KASPR) samples fine-scale fire-atmosphere interactions within ash and debris plumes of wildfires. KASPR is a fully-scanning, dual-polarimetric millimeter wavelength radar suited for studying clouds, small hydrometeors, and ash lofted by wildfires. KASPR operates at 35.61 GHz with a solid-state power amp that has apeak power of 10 W and an antenna with a diameter of 1.8 m. This unit is comprised of a radartransmitter, antenna, vertically scanning pedestal, control software, digital receiver, and an electronics enclosure. The radar unit is mounted on the bed of a Ford F-250 4x4 pickup truck (Fig. 22). The design of the radar unit allows for rapid deployments to fires using the"storm chaser" approach that is widely used in the severe weather community (Bluestein 1999).

5.3.3 Results

In this section, only Doppler lidar and radar results will be presented. At this point in the study these results are not intended to be fully developed scientifically, rather, illustrative examples of plume processes that have implications for plume rise and fire behavior.

Doppler lidar measurements detected both the over-all plume structures, a portion of the mixing processes, and presence of vortical entrainment structures (Fig, 22). Microscale entrainment structures in convective plumes including scale and strength of horizontal axis "ring vortices" were observed and documented in addition to smoke-induced density currents that formed because of reduced insolation beneath smoke layers. Furthermore, strength, scale, and evolution of vertical axis hole column rotation within a plume was observed and documented.



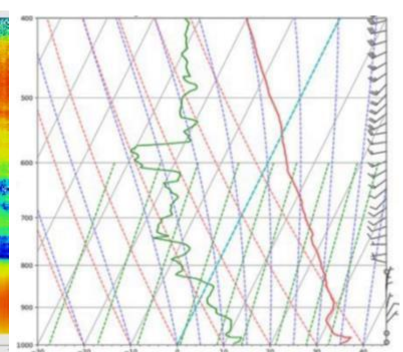


Figure 22. Doppler lidar backscatter and radiosonde skew-T during Carr Fire 28 July 2018 showing 1750 m deep smoke layer with a super-adiabatic layer within the plume. Secondary inversion layer is also present in the middle lower plume layer at 900 mb.

Dual polarimetric Ka-band radar measurements were used to observe the fine-scale kinematics and microphysical properties of smoke plumes.This study highlights the advantages of utilizing a portable, millimeter wavelength radar for monitoring and investigating wildfire plume dynamics and microphysics. Through the analysis of radar reflectivity, radial velocity, and polarimetric properties, insight into Ka-band radar specific signatures of smoke plumes are shown. Distributions of radar reflectivity were similar across all deployments, revealing values between -15 and 20 dBZ within the plume and some reflectivity cores exceeding this upper limit. Areas of maximal reflectivity were associated with maxima in radial velocity and Doppler spectrum width and were located near the base of the plume and updraft zone for all plumes sampled. Radial velocity structures revealed converging flow into plume bases and diverging flow aloft, while clean air entrainment was observed in the radial velocity signatures from the Kincade D1 and D2 and Langdon Mountain (Fig. 23).

The observed polarimetric parameters were similar to those of previous studies using radarto investigate polarimetric properties of wildfire plumes. Positive values of *ZDR* paired with low *ρhv* indicate wildfire targets are of various shapes and sizes in each sample volume. Positive *ZDR*values were associated with low reflectivity values and remained outside of the primary updraft location, with maximum values near 6 dB. Correlation coefficient values remained below 0.8 for in plume observations, with the lowest values (~ 0.3) located near plume base.

5.3.4 Conclusion

The results from this study highlight the high temporal and spatial resolution observationsof wildfire smoke plumes obtained from millimeter wavelength radars. Further investigation intothe fine-scale kinematics and microphysical properties of wildfire smoke plumes will aid in the development and validation of better predictive tools for wildfire behavior by incorporating these types of observations into next-generation spotting and ember transport models.

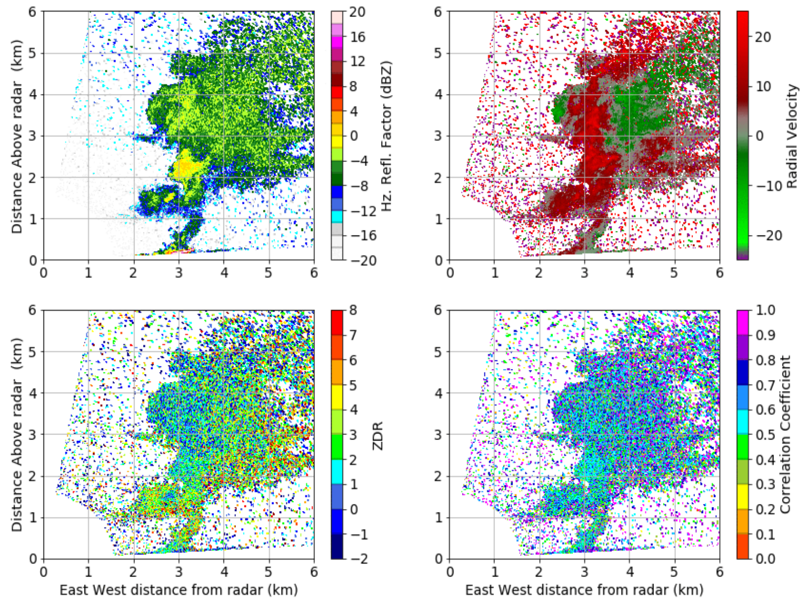


Figure 23. Doppler radar imagery captured from the Langdon Mountain stand replacement fire during the SW campaign.

5.4 Smoke

5.4.1 Background

The original FASMEE Study Plan included airborne measurements of smoke constituents and conditions around and within the smoke plume as major elements of the datasets to be collected. The development of these elements of model input data proceeded through the design of a detailed Measurements Specifications Document describing and prioritizing the types of data that would provide the most helpful inputs to drive model evolution. In addition, biological aerosols, which include multiple respiratory irritants, are considered one of the major unknowns in modeling impacts associated with wildland fire smoke, and they have yet to be integrated into smoke modeling systems. This was added as part of the suite of ecological studies associated with FASMEE project and directly addresses elements of the overarching FASMEE science question: "*How do fuels, fire behavior, fire energy, and meteorology influence the dynamics of near-source plumes and the process of long-range transport of smoke and its chemical evolution?"*

Measurements collected from airborne platforms were the most desirable, and coalesced around those collected from large, crewed aircraft and those collected aboard small, unmanned aircraft systems (UAS). With the exception of airborne LiDAR surveys that aided Fuels and other disciplines, the transition from planning to execution saw a combination of platform availability issues and funding shortfalls which impacted our ability to use large, manned aircraft for airborne data collection. These challenges led to an emphasis on using UAS to gather data at the scales most suited to the operating altitudes and flight durations of these platforms. While off-the-shelf instruments have been available for the collection of airborne imagery by UAS for several years, a lack of atmospheric measurement capacity was identified as a challenge to be overcome.

5.4.2 Methods

Two primary challenges presented themselves at the outset of the Smoke Discipline's work. The first of these was the development of operational UAS capacity sufficient to serve the data needs of FASMEE, but within budget limitations. Fortunately, other sponsored research projects enabled an expansion of the UAS fleet, while careful coordination across the Region and National UAS Program Office led to the successful development of a Project Aviation Safety Plan and protocols for UAS use that received approval and allowed operations over the complex burns at Fishlake NF.

The second challenge was the absence of suitable atmospheric sensors for making airborne atmospheric and smoke measurements. Support from FASMEE both catalyzed and funded the development of a miniaturized multi-sensor payload system intended for use aboard small UAS. This first-of-its-kind development created a unique ability to characterize smoke plumes at low altitudes above an active fire, with high spatial precision and without any risk to human pilots or crew.

One specific smoke constitute that was measured using UAS were bioaerosols sampled through an array of instrumentation while simultaneously measuring PM, smoke, and fire behavior. We then used molecular and microscopy techniques to analyze community composition, microbe viability, and ice nucleation potential of the bioaerosols as a function of environmental variables. These data were analyzed in the context of the fire behavior, plume dynamics, and soil heating data being collected by other FASMEE researchers, thereby leveraging the collaborative potential for revealing the patterns and processes driving smoke-microbe transport.

5.4.3 Results

The Smoke Discipline was able to collect airborne smoke measurements at Manning Creek and Annabella Reservoir burns in 2019 and 2020 as one ultimate outcome. This success was the result of both building operational capacity and also the design, development, and prototyping of the "multi-pollutant sensing system" payload (Nelson et al. 2019), each being significant achievements in their own right. The data that were collected have been quality-control checked, and will be made available for future use along with other FASMEE datasets according to the Data Management Plan.

A significant outcome from the Smoke Discipline work that was unforeseen at the outset was the development and testing of the hypothesis that wildland fires can entrain and transport biologically viable microorganisms in their plumes (Fig. 24). The Fishlake burns provided the first opportunity to conduct work in this new sub-discipline at the crossroads of microbiology and fire science. These achievements have resulted in a number of peer-reviewed publications, presentations, and workshops describing this "pyroaerobiology" work (Kobziar et al. 2022).

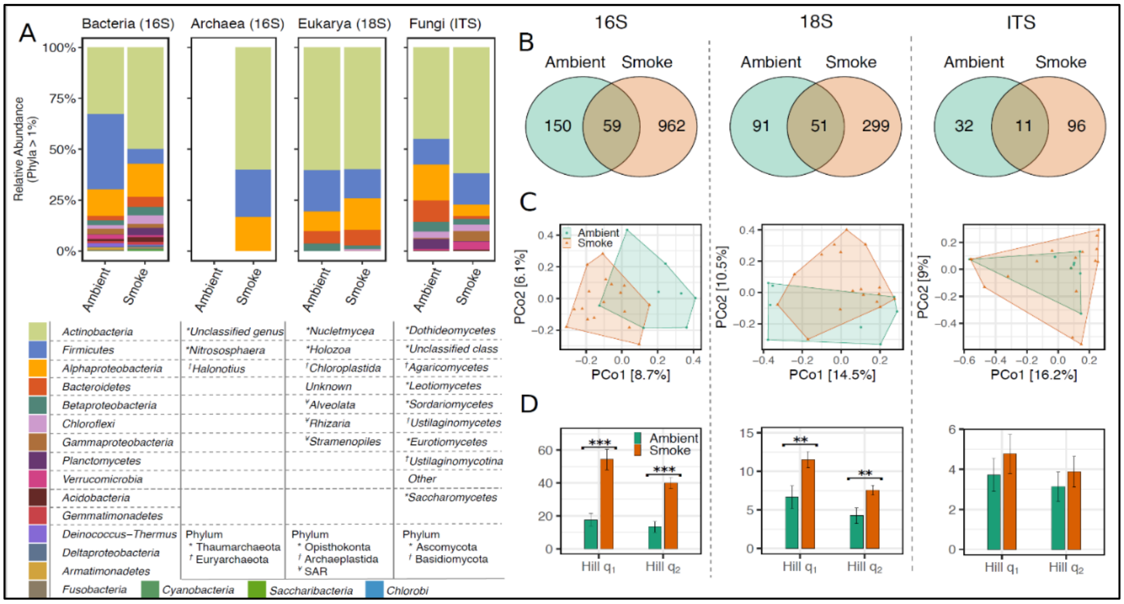


Figure 24. At the Manning Creek burn, nearly four times as many cells were aerosolized by the fire as those found in background air. Diversity in smoke was double that of ambient air.

5.4.4 Conclusion

The ability to leverage FASMEE and additional projects against one another to develop, prototype, and operationalize a new instrument system and explore a new line of scientific inquiry represents a rare best-case combination of opportunity, creativity, and good fortune. The productivity of this discipline and that of other teams also illustrates the potential for synergistic outcomes when a project is carefully planned and coordinated.

Future measurement of smoke characteristics has been advanced significantly by the development of new instruments and the operational protocols and capacity that FASMEE has enabled. The results of this foundational work will be an increase in spatial and temporal resolution of airborne measurements, not only of smoke but also of linked observations of fire behavior and effects. The ability of the team to collect these measurements for a fraction of the cost of human-crewed aircraft without any safety risks to people showcases the important aspects of UAS work on fires. However, the future incorporation of large airborne platforms will remain essential due to their ability to operate at high altitudes and collect measurements both deep within the plume and far downwind, and to make observations of large areas in one imagery scene.

FASMEE smoke measurements during future campaigns will include both platform types, so that measurements from the high-altitude platforms can be fused with those collected at low altitudes and at fine resolution. These rich datasets will enable the simultaneous evolution of models across a range of time and space domains. It is the ability of Unmanned Aircraft Systems to simultaneously provide the full variety of data important to fire and smoke model evaluation and advancement.

5.5 Fire Effects

5.5.1 Background

At its inception, FASMEE did not include nor fund co-measurement of fire effects in spite of the strong regional and national interest and the added value of linking FASMEE measurements to better understanding fire effects. This JFSP support represented seed funds to coalesce a Fire Effects Team, plan measurements, and collect data on several FASMEE burns at the Fishlake National Forest in 2019 and 2020 and enables post-fire measurements over the coming years.

The overarching research questions for Fire Effects focused on the ecological responses of forests to variation in fire behavior. The forested communities of the Fishlake National Forest are dominated by quaking aspen (*Populus tremuloides*), Englemann spruce (*Picea engelmannii*), and subalpine fir (*Abies lasiocarpa*), three fire-sensitive tree species that succumb to fire injuries rapidly (Fig. 25). The conifers tend to have deep crowns that serve as ladder fuels for surface fires and lack any adaptations to survive the intense stand-replacing fires that are typical of prescribed and wildfires in the Fishlake and more broadly in the region (Alexander and Shepperd 1984, Stevens et al. 2020). Among these three, quaking aspen is unique due to its abundant post-fire vegetative suckering (Fig. 26). Indeed, the primary management objective of the prescribed fire program in the Monroe Mountain area is to regenerate quaking apsen via suckering and to improve elk (*Cervus elaphus*) and mule deer (*Odocoileus hemionus*) habitat, as well as to improve forage for cattle. Next generation fire effects research requires linking observed ecological responses to detailed, spatially explicit fuels, weather, and smoke measurements measured during FASMEE campaigns. FASMEE's Southwest Campaign offered the opportunity to evaluate post-fire suckering response of quaking aspen and to delve into post-fire mortality of all three dominant tree species.

Figure 25. Post-fire mortality of overstory conifers and quaking aspen, Fishlake National Forest.

Figure 26. Abundant post-fire suckering of quaking aspen, Fishlake National Forest.

Post-fire suckering has primarily been evaluated in pre- vs. post-fire comparisons, preventing our ability to link suckering response to fire with the intervening fuels and fire behavior that caused the suckering response. Aspen regeneration is well-known for its variation, likely due to genetic variation among clones, variability in fire behavior, differential herbivory, and its interactions with invading conifers. Past work failed to measure fuels and fire behavior at the intensity that of FASMEE, leaving lingering questions on how fire interacts with the other drivers of post-fire sprouting. The 2019 and 2020 campaigns offered a unique opportunity to leverage unprecedented fuels and fire behavior data of aspen regeneration response.

Our research questions focused on aspen suckering response and the underlying mechanisms of observed patterns in suckering. Our design in the Manning Creek, Langdon Mountain, and Annabella Reservoir burns was based on a lattice of biotic and abiotic factors that may influence suckering responses. Ultimately, we sought to determine the relative roles of three drivers of suckering response:

- What role did differences in aspen genetics play in suckering response (sucker density and height)?
- What effect did pre-fire conifer encroachment (via relative basal area and density) and subsequent mortality have on aspen suckering response (sucker density and height)?
- How did local fire behavior and fuel consumption affect aspen suckering response?
- How did topographic variability (via composite heat load index; McCune and Keon 2002) add to or minimize variation in aspen suckering response? and
- What was the relative effect of these four potential drivers on suckering response and ultimately, post-fire stand composition and structure?

These funds provided a first step toward answering these questions while also contributing to the overall FASMEE campaign.

5.5.2 Methods

We selected aspen plots pre-fire at Manning and Annabella, and opportunistically post-burn at Langdon Mountain. In each 201 m^2 (8 m radius) plot, we measured plot slope, aspect, and elevation to characterize the abiotic exposure (as in McCune and Keon 2002); 20 plots at Manning, 45 plots at Annabella, and 10 plots at Langdon Mountain. Within each plot, we identified, measured, and stem-mapped all overstory trees (> 10 cm diameter at breast height). From these measurements, we calculated the degree of conifer encroachment (as % basal area and density; composite importance value). Additionally, we used a Reigl Terrestrial Laser Scanner to image pre- and post-ire plots (Fig. 27). Following fires, we remeasured all plots to assess post-fire mortality of overstory trees by species. We also counted post-fire aspen suckers within a 12.6 m^2 (2 m radius) nested subplot in each plot.

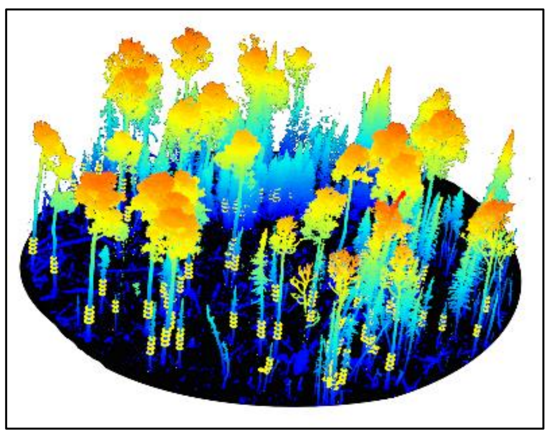


Figure 27. Pre-fire terrestrial plot laser scan within Annabella unit showing segmented individual trees. Yellow rings around stems indicate individual stems identified by the algorithm.

To isolate potential genetic effects, we sampled foliage from aspen suckers at Manning and Annabella. This sampling entailed removing leaves from a sucker and storing in labeled bags in silica gel desiccant. These samples were then shipped to the Molecular Ecology Laboratory at Utah State University for DNA extraction and analysis. To isolate potential effects of soil heating on suckering response and to add to plot-level estimates of fire severity, we buried thermocouples 10 cm below the surface in a subset of plots at Annabella (135 plots with thermocouples). We used Lascar dataloggers (Omega 20 gauge, Type K) and measured maximum temperature at 5 minute intervals beginning before, during, and one month after the burn.

5.5.3 Results

The Fire Effects discipline's major research has been concentrated post-fire, and with COVID travel and work restrictions were delayed until summer 2021. We provide preliminary results here and will update JFSP on all results as the data continue to be collected and analyzed in FY 22 and FY 23.

5.5.3.1 Tree Mortality and Suckering

Pre-fire, the stands sampled varied in density and basal area and representation by quaking aspen and the two co-dominant conifers. Post-fire tree mortality varied across the three burns (from 100% mortality to 0% in unburned plots). At Manning Creek, the more uniform high severity fire resulted in near 100% tree mortality for all measured plots. Within the mixed-severity Annabella unit, mortality was patchy; higher for the two overstory conifers (mean = 35.6 % and 37.1 % of basal area) than quaking aspen (mean = 22.5 % and 21.8 % of basal area; Table 4). We will continue post-fire mortality surveys at all three sites in FY 22 to capture delayed mortality. Post-fire aspen sucker density was highly variable. Post-fire sucker density averaged 6,883 suckers ha^{-1} (std. dev. = 1,706). All measured "seedlings" of quaking aspen were of sucker origin. We will continue sampling of aspen suckers, conifer seedlings, and determination of sucker vs. seedlings for aspen in the future.

Table 4. Overstory tree mortality from the Annabella unit at the Fishlake National Forest, Utah. Values in parentheses are standard deviations around the mean.

	Overstory (trees ≥10 cm DBH)				
Species	**Pre-burn density** (*trees ha^{-1}*)	**Pre-burn BA** (*m^2 ha^{-1}*)	**Mortality (density)** (%)	**Mortality (BA)** (%)	**BA killed** (*m^2 ha^{-1}*)
Aspen	693 (358)	38.0 (15.7)	22.5 (36.1)	21.8 (36.1)	9.0 (13.3)
Conifers	302 (225)	10.5 (8.0)	35.6 (45.0)	37.1 (46.0)	3.6 (6.1)

5.5.3.2 Aspen Genetics

We found high variability in pre-fire quaking aspen clone diversity at Manning Creek. The genetic sampling detected 14-32 clones across the 178 samples and plot network, with three clones covering 47% of the sampled suckers (Fig. 28). The remaining clones had fewer than 10 samples per clone. Of the samples sequenced, 35 were diploid cytotype and 139 were triploid. Sex identification resulted in 70% male and 29% female aspen clones. Aspen tissue samples were collected at the Annabella site as well, but funding was not available for processing. We plan to sample post-fire suckering at all three sites in FY 22.

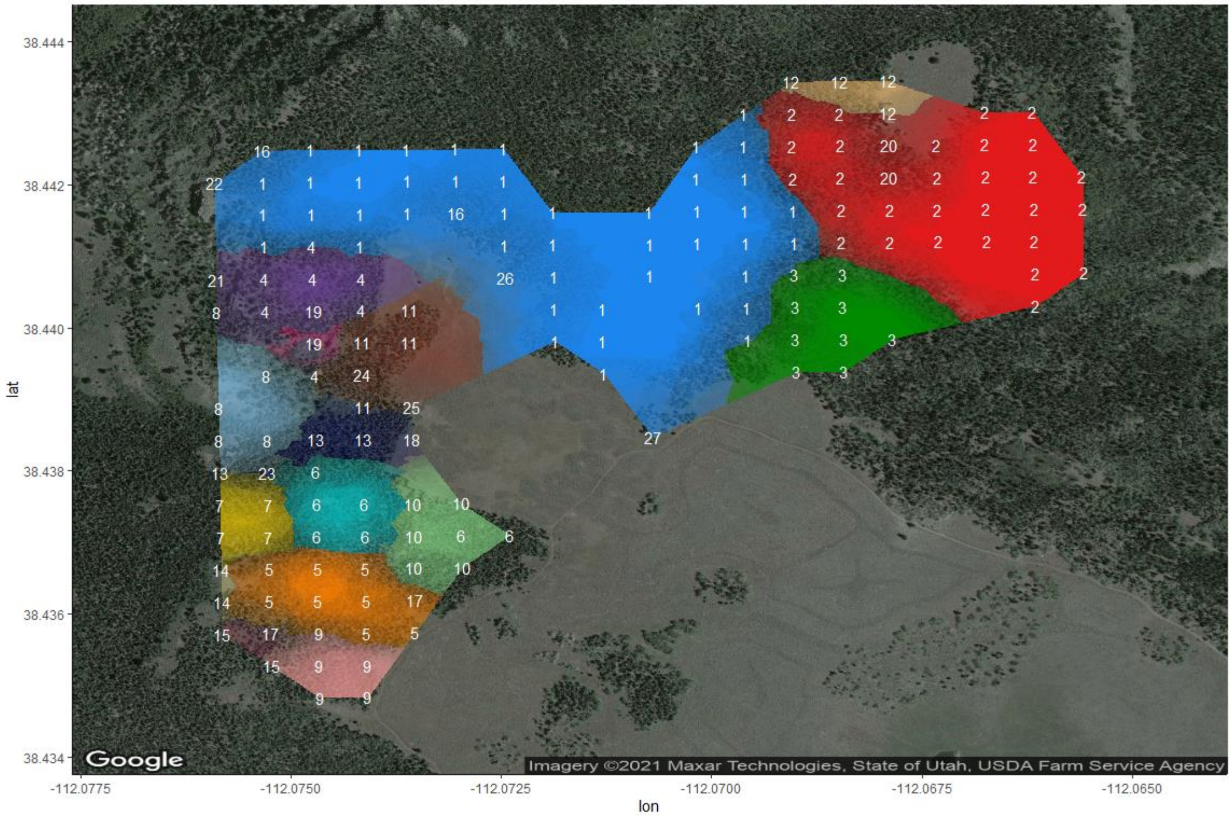


Figure 28. Map of aspen clone distribution at Manning Creek in the Fishlake National Forest, Utah. Numbers represent locations where aspen tissue samples were collected and the corresponding clone ID. Colors represent the most probable interpolated clone identity using a weighted k-nearest neighbor classifier. More opaque colors have a higher probability of belonging to the corresponding clone ID.

5.5.3.3 Soil heating

We observed substantial soil heating in the Annabella burn, and substantial variation. We found wide variability in soil heating, with maximum recorded temperatures ranging to 571° C. Duration of lethal heating (using hours above 60° C, presumed lethal threshold temperature) averaged nearly 3 hours and ranged from 0 to 17.83 hours (Table 5). Analysis of these data continues and relationships between heating and measured woody and forest floor consumption is planned.

Table 5. Soil temperatures measured at 10cm beneath soil surface (FERA and Fire Effects plots).

	Mean	**Std Dev**	**Range**
Maximum Temp (°C)	88	129	1 – 571
Duration ≥ 60 °C (hours)	2.97	4.94	0 – 17.83

5.5.4 Conclusion

Pre-fire, the stands sampled varied in density and basal area and representation by quaking aspen and the two co-dominant conifers. Post-fire tree mortality varied across the three burns (from 100% mortality to 0% in unburned plots). We found high variation in pre-fire quaking aspen clone diversity at Manning Creek. The genetic sampling detected 14-32 clones across the 178 samples and plot network, with three clones covering 47% of the sampled suckers. We observed substantial soil heating in the Annabella burn. We found wide variability in soil heating, with maximum recorded temperatures of 571° C, and duration of lethal heating averaging ca 3h and ranging from 0 to 17.83h.

Our planned FY 22 and 23 sampling will re-survey all plots at Manning, Annabella, and Langdon Mountain. We will compare soil heating to aspen suckering at the plot level across all measured plots. These data will be combined with site variables (as in McCune and Keon 2002), degree of pre-fire conifer encroachment (% basal area and % density), and overstory post-fire mortality to compare aspen sucker height and density (suckers ha^{-1}). In sites where we have aspen genetics data, we will compare suckering response (height and density) across the variation in genetic identity. Post-fire overstory tree mortality surveys will continue in FY 22 and FY 23. We will compare mortality across species (two conifers and quaking aspen) and develop mortality models for all three species across the ranges of diameters surveyed.

6. FASMEE Southeast Campaign

Planning for the FASMEE southeast data collection campaign was initiated in 2016, and secured Fort Stewart as a host agency. Four prescribed burn sites were selected for sampling. However, with a shortfall of funds and delay in the campaign initiation, the SERDP Integrated Management Research Team (IRMT) took control of the logistics and planning of the research burns for their SERDP fire projects. FASMEE was invited to participate and will be in attendance with the fuel, fire behavior and energy, plume dynamics, and fire effects disciplines collecting data. The burns are scheduled for the first week of March, 2022.

7. Overall Discussion

As wildland fire models have become more sophisticated, there has been an increasing need for complex datasets that are coordinated, synchronized and comprehensive. Desired metrics range from ground-based observations of fuels, fuel consumption, and fire behavior and energy, to near-source plume dynamics and energy, smoke concentration and trajectories, dispersion, atmospheric chemistry, smoke aging, and vegetation response. FASMEE is designed to provide these integrated observations, and to serve as a template for future campaigns that together will provide the datasets necessary to evaluate and develop next-generation operational fire and smoke modeling systems.

Building on the success and lessons learned from previous fire and atmospheric campaigns such as the Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE) and Northwest Crown Fire Experiment, the FASMEE project was launched to provide integrated measurements of high-intensity fire behavior and smoke in both the western and eastern regions of the United States. FASMEE takes advantage of past campaigns, including the importance of involving fire scientists and model developers at the inception of measurements campaigns, and the critical value of spatiotemporal synchronization of all measurements identified.

The FASMEE study plan assessment indicated that the Phase 2 data collection would cost approximately 8 million dollars over the course of 5 years. However, only partial funding was available from the JFSP. Consequently, to keep FASMEE moving forward, those funds were leveraged with other agencies, including in-kind support from the National Science Foundation, NOAA, and NASA and funding from the U.S. Forest Service Pacific Northwest Research Station, US Forest Service Fire and Aviation Management of the Washington Office and EPA. Additionally, many scientists contributed their own time and resources to participate in this effort. This combined support provided continued leadership for FASMEE and initiated a reduced effort for the Phase 2 western wildfire data collection campaign.

The future of FASMEE looks bright. The US Forest service Washington Office selected the FASMEE proposal for $1,000,000 of funding in FY22, FY23, and FY24. Although full funding of FASMEE has yet to be secured, the study plan along with the Phase 2 data collection provides a compelling case for investment in large-scale, comprehensive measurement campaigns of fuel, fire, smoke, and other fire effects.

8. Conclusions Including Key Findings and Progress

Significant advances in our understanding of fire and smoke dynamics as well as our ability to observe, characterize and model fuels, fuel consumption, energy release, fire behavior, plume dynamics, smoke production and aging, and dispersion have been made over the past decade. Advanced model output is now routinely available to managers, as seen with the incorporation, use and adoption of the BlueSky modeling framework and the Interagency Fuel Treatment Decision Support System (IFTDSS). These systems provide value added information but are simplistic in their treatment of complex fire dynamics and need to be thoroughly evaluated and advanced. More complex models, such as coupled fire-atmosphere-chemistry models (e.g., WFR-SFIRE-CHEM, WFDS and FIRETEC) are being developed, but are not in full operative mode currently and will require greater input data. Unfortunately, the lack of observational data means substantial uncertainty about the underlying dynamics and how well these systems can capture them. FASMEE is designed to facilitate the transition of more advanced modeling systems into operational use by supplying critical data necessary to evaluate and advance these systems. The expected outcome from the FASMEE project (assuming adequate funding and support) include:

- Improvements in our scientific knowledge of the physically-coupled fuels-fire-smoke-chemistry system,
- Improved methods for measuring fuels for fire spread, fuel consumption and fire emissions models,
- Insight into processes that drive the spatial organization of fire energy and emissions to help define the transition between fires and plumes that affect air quality, and
- Improvement of existing operational fire and smoke models and the development of new models based on the collection of a unique dataset (fuels, fire, meteorological, smoke plume and chemistry, fire effects).

The three FASMEE campaigns, as outlined in the study plan deliverable, have started to provide the referenced, synchronized fuel, fire behavior and energy, plume dynamics, meteorological and emission, and fire effects data required for the evaluation and advancement of operational fire and smoke modeling systems in current use. These data are becoming available to all individuals through an open data repository designed by geospatial data managers and coordinated with partner agencies to ensure the development of a legacy dataset that can be amplified in subsequent coordinated field campaigns.

8.1 Value for Assessment and Advancement of Operational Fire and Smoke Models

Software tools currently in use today that drive smoke model prediction systems and are expected to use data collected during FASMEE to assess and advance these models. These include modeling systems (e.g., FIRETEC, WFDS, WRF-SFIRE, MesoNH-ForeFire, Daysmoke and the BlueSky framework, WRF-SFIRE and the Community Multiscale Air Quality (CMAQ)) that quantitatively predict smoke and estimates of smoke particulate concentration and trace gases. The significant knowledge gaps in smoke modeling include (1) how the composition and intensity of emissions vary with fuel characteristics and fire behavior, (2) how fire-generated buoyant flow combines with ambient atmospheric conditions to develop smoke plumes, and (3) understanding of post-emission chemical processes that can rapidly cause large changes in the concentrations of fine PM and O_3. The only means to satisfactorily address these gaps is through sufficient measurements of area burned, fuels, fuel consumption, fire behavior, fire-generated heat, and smoke production, transport, and evolution, which can then be used to test model parameterizations and evaluate the results.

The FASMEE-recommended measurement suite is designed to collect data for the critical factors in the production, transport and chemical evolution of smoke. Phase 2 recommendations emphasize measurements of high-volume smoke production from burning in heavy fuels that produce multiple plume cores and significant vertical plume development. The mass of smoke produced and the plume dynamics will mimic those of a robust wildfire, producing a plume sufficiently concentrated to observe photochemical evolution and atmospheric transport similar to that of wildfires. The resulting data can be applied to nearly any modeling system with a smoke prediction component.

8.2 Benefit to Fire and Smoke Management Community

The measurement suite planned for FASMEE provides quantitative information for improvements and development of many coupled fire-atmosphere models and will provide critical datasets for developing the next generation of operational models of fire and smoke. For models currently used for research-based analyses of fire, FASMEE will provide uniquely integrated and comprehensive datasets to advance our understanding of the complex fire-atmosphere system. Integrated measurements from the FASMEE campaign will enable evaluations of (1) how well specific models perform under real-world applications, (2) the level of model uncertainties, and (3) what key sources of these uncertainties need improvements. Observation-based phenomenological characterization can help to assess whether intermediate-complexity and physics-based models are capturing coupled fire-atmosphere behavior that is critical to the simulation of high-intensity fires in complex terrain.

8.3 Broader Impact onto Decision Makers and Society

Many sources for smoke information are now available to managers, including both web-based and downloadable models and datasets. These include simple screening tools, ventilation indices, web-based systems, real-time smoke forecasts, and daily atmospheric chemistry modeling. These resources are commonly used to help mitigate smoke effects, which can be numerous. Smoke from wildfires has been associated with increased physician and emergency room visits, hospital admissions, and mortality. Illnesses and infectious disease complications (e.g. Covid-19) attributed to smoke exposure can also result in hospital admissions and absenteeism from work and school, affecting economic productivity and educational achievement. The FASMEE project aims to provide data that will improve publicly available information generated from smoke models for the protection of public health and welfare through more accurate smoke predictions and warnings.

The scope and design of the FASMEE field experiments allows for interagency collaboration and partnerships. For example, agency programs that focus on air quality could use methods similar to those recommended for the Phase 2 measurement campaign to characterize fuels, fire behavior, and plume dynamics.

This experiment will serve as a training opportunity for investigators in the earlier stages of their careers to observe and participate in large research burns that involve close coordination among managers, researchers, and operations communities. In the same way that the research outcomes of FASMEE benefit research support to fire management in the coming decades, the experience provided to early-career personnel involved in FASMEE will benefit the research community's ability to plan, coordinate and conduct ambitious projects in other areas of fire science well into the future.

8.4 Broader Effects on Other Disciplines

Data from the FASMEE research burns will provide large data sets that will be available for use by many other disciplines besides fire and smoke science. Ecological measurements could be made pre- and post-burn in the context of detailed known fire environment and burning conditions that can be associated with ecological effects. Documentation of FASMEE burns will include spatiotemporal mapping of fuels, fuel consumption, fire behavior, heat release and duration, plume development to facilitate broad use of the datasets collected during these campaigns.

Depending on the ecological focus, additional insights provided by fuel consumption and heat duration data from the FASMEE could include studies of tree mortality or aspen spouting. U.S. Geological Survey Forest and Rangeland Ecosystem Science Center studies of soil and erosion will benefit from detailed observations of pre- and post-fire fuel characterization and energy release over time. Although FASMEE will not provide the resources to assist with or participate in such studies, the FASMEE leadership team and investigators have expressed a desire to cooperate with interested non-FASMEE teams in conducting work that will not interfere with FASMEE logistics or add personnel or complexity during the burns themselves.

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Appendix A--Contact information for Key Project Personnel

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Appendix B. List of Completed/Planned Scientific/Technical Publications/Science Delivery Products

1. JFSP FASMEE Phase 1 Final Report

Fire and Smoke Model Evaluation Experiment (FASMEE) JFSP Final Report for Phase 1 https://drive.google.com/file/d/1wQnnCxiMNmC6SvMZuozj-dO7znCEipiw/view

2. FASMEE Study Plan Publications

Fire and Smoke Model Evaluation Experiment (FASMEE) Study Plan: https://drive.google.com/file/d/1KHwBiQFY6nqExDRBu0pWZGNI7sgV89oy/view

Liu, Y, Kochanski, A, Baker, K, Mell, R, Linn, R, Paugam, J. Mandel, A, Fournier, MA, Jenkins, Goodrick, S, Achtemeier, G, Zhao, R. Ottmar, N. French, N. Larkin, N, Brown, T. Hudak, A, Dickinson, M, Potter, P, Clements, C. Urbanski, S, Prichard, S, Watts A, and McNamara, D. 2019. Fire behavior and smoke modeling: Model improvement and measurement needs for next-generation operational smoke prediction systems. *International Journal of Wildland Fire* 28(8) 570-588. https://doi.org/10.1071/WF18204. **Selected as 1 of 15 key review papers for a new virtual issue of IJWF, celebrating 30 Years of Wildland Fire Science Publication.**

Prichard, SJ, Larkin, N, Ottmar, RD, French, NH, Brown, TJ, Baker, K, Clements, C, Dickinson, M, Hudak, A, Kochanski, A, Linn, R, Liu, Y, Potter, B, Mell, WE, Tanzer, D, Urbanski, S, Watts, AC (2019). The Fire and Smoke Model Evaluation Experiment: A plan for integrated, large fire-atmosphere field campaigns, *Atmosphere*, 10, (2), 66, https://doi.org/10.3390/atmos10020066. https://www.fs.usda.gov/treesearch/pubs/57718

3. FASMEE Western Wildfire Campaign Publications

Bright, BC, Hudak, AT, McCarley, TR and Spannuth, A. (In Prep) Multitemporal lidar captures heterogeneity in fuel loads and consumption achieved by active fire managers on the Kaibab Plateau. *Fire Ecology*.

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McCarley, TR, Hudak, AT, Restaino, JC, Billmire, M, French, NH, Ottmar, RD, Haas, B, Goulden, T and Volkamer, R. (In Prep) A comparison of multitemporal airborne laser scanning data and the Fuel Characteristics Classification System for estimating fuel load and consumption. *Journal of Geophysical Research-Biogeosciences*.

McGaughey, RJ 2018. FUSION/LDV: Software for LIDAR Data Analysis and Visualization, v3.80. USDA Forest Service, Pacific Northwest Research Station, Seattle, WA.

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Hood, SM, K. Mock, Shearman, TM, Kreye, JK and Varner, JM. (In Prep) Genetic, fire severity, and topographic drivers of post-fire suckering of *Populus tremuloides*.

Kobziar, LN, Pingree, M, Watts, AC, Nelson, KN, Dreaden, TJ, and Rideout, M. (2019). Accessing the life of smoke: using small unmanned aircraft systems (UAS) to sample wildland fire bioaerosol emissions and their environment. Fire 2(4):56.

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Nelson, KN, Boehmler, JM, Khlystov, AK, Moosmüller, H, Samburova, V, Bhatterai, C, Wilcox, EM, and Watts AC. 2019. A Multipollutant Smoke Emissions Sensing and Sampling Instrument Package for Unmanned Aircraft Systems: Development and Testing. Fire 2: 32.

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Toolan, MJ, Kreye, JK, Shearman, TM, Hood, SM, and Varner, JM. (In Prep) Diversity of post-fire suckering by *Populus tremuloides* across a fire intensity gradient.

Watts, AC., Samburova, V, and Moosmüller, H. 2020. Criteria-based identification of important fuels for wildland fire emissions research. Atmosphere 11:640; 10.3390/atmos11060641. (*Selected for Editor's Choice Award*).

5. Theses and Dissertations (in progress)

Toolan, MJ 2022. Post-fire quaking aspen suckering in high intensity prescribed fires in Utah, USA. The Pennsylvania State University, Thesis.

6. Joint Fire Science Program Assistance

Ottmar, Roger; Larkin, Sim, Brown, Tim. 2015. Notice of Intent for 2016 Funding Opportunity for FASMEE Phase 2 observational measurement collection

Ottmar, Roger, Larkin, Sim, Brown, Tim. 2015. Funding Opportunity Notice for fall of 2016 for FASMEE Phase 2 operational measurement collection

7. Presentations

Brewer, M, Watts, AC. Clements, C. (2019) Small UAS for Fire Weather and Fire Behavior Monitoring in the Wildland Fire Environment. Presentation, 8th International Fire Ecology and Management Congress, 18-22 November 2019, Tucson, AZ.

Brewer, M., Clements, C and Watts, A. (2020) Small UASs for fire weather and fire behavior monitoring in the wildland fire environment. Presentation, 100th American Meteorological Society Annual Meeting, 12-16 January 2020, Boston, MA.

Bright, BC, Hudak, AT, McCarley, TR, and Spannuth, A. (2021) Mapping fuel dynamics with airborne lidar and field observations in Kaibab National Forest, Arizona. Association for Fire Ecology Congress, 30 Nov – 4 Dec 2021. (virtual oral presentation, published abstract).

French, N, Ottmar, R, Brown, TJ, Larkin, N, Prichard, S and Watts, AC. (2017) Fire and smoke model evaluation experiment (FASMEE): Coordination of a study to improve smoke modeling for fire operations within the United States. Poster, American Geophysical Union Fall Meeting, 11-14 December 2017, New Orleans, LA.

French, N. (2020) Remote Sensing for quantifying wildland fire: A case study of the 2019 Williams Flats Fire". Presented by NHF French at the 3rd International Smoke Symposium, April 22, 2020 (virtual).

French, N. (2021) Characterizing the Wildland Fire Environment for Smoke Modeling and Air Quality Mapping". Presented by NHF French at American Geophysical Union 2021 Fall Meeting, December 17, 2021, New Orleans, LA.

Halverson, K and Hudak, A. (2019) Applications of carbon and biomass data in the USDA Forest Service. Carbon Monitoring Systems Applications Workshop, La Jolla, California, 12 Nov 2019. (oral presentation).

Hudak, AT and Halverson, K. (2020). Rating the effectiveness of treatments: biomass products. USFS Region 4 Information Management Meeting, Ogden, Utah, 13-15 Apr 2020. (virtual oral presentation).

Hudak, A, McCarley, R, Bright, B, Corrao, M, Ottmar, R, French, N and Soja, A. (2020). FASMEE Western Wildfire Campaign: Fuel consumption maps to reduce uncertainties in emissions. Third International Smoke Symposium, Raleigh, North Carolina, 20-23 Apr 2020. (virtual oral presentation, published abstract).

Hudak, A, McCarley, R, Fekety, P, Mauro, F, Kane, V, Restaino, J, Ottmar, R, Fischer, E, Volkamer, R, Goulden, T and Haas, B. (2019). FASMEE Western Wildfire Campaign: Modeled, ground, and lidar based estimates of fuel consumption. 8th International Association for Fire Ecology Congress, Tucson, Arizona, 18-22 Nov 2019. (oral presentation, published abstract).

Hudak, A, Fekety, P, Filippelli, S, Falkowski, M, Kennedy, R, and Kane, V. (2019). Annual (2000-2016) maps of aboveground biomass in the Northwestern USA. International Union of Forestry Research Organizations World Congress, Curitiba, Parana, Brazil, 29 Sep – 5 Oct 2019. (oral presentation, published abstract).

Hudak, A (2019). Carbon Monitoring System (CMS) Phases 1 and 2. Operational Lidar Inventory Workshop, Olympia, Washington, 5 Mar 2020. (oral presentation).

Hudak, A, Fekety, P, Falkowski, M, Kennedy, R and Kane, V. (2019). Upscaling of project-level, lidar-based forest inventories for regional biomass mapping in the northwestern USA. National Silviculture Workshop, Bemidji, Minnesota, 21-23 May 2019. (poster, published abstract).

Hudak, A, McCarley, R, Restaino, J, Ottmar, R, Goulden, T, Volkame, R and Fischer, E. (2019) Fuel consumption and emissions on the five WE-CAN/BB-FUX wildfires selected for field and airborne LiDAR measurements. Western Wildfire Smoke Workshop, Boulder, Colorado, 23-25 Apr 2019. (oral presentation).

Hudak, A, Bright, B, McCarley, R, Kato, A, Loudermilk, L, Hawley, C, Prata, G, Prichard, S, Restaino, J, Ottmar, R and Weise, D. (2019). Estimating fuel consumption at multiple scales from pre- and post-fire TLS and ALS. Silvilaser Conference, Foz do Iguacu, Parana, Brazil, 8-10 Oct 2019. (oral presentation, published abstract).

Hudak, A., McCarley, R, Fekety, P, Mauro, F, Kane, V, Restaino, J, Ottmar, R, Fischer, E, Volkamer, R, Goulde, T and Haas, B. (2019) FASMEE Western Wildfire Campaign: Modeled, ground, and lidar based estimates of fuel consumption. 8th International Association for Fire Ecology Congress, Tucson, Arizona, 18-22 Nov 2019. (oral presentation, published abstract).

Hudak, AT. (2020) Benefits of coordinated data management and archival for advancing fire science. Wildland Fire Technical Session, SERDP-ESTCP Symposium, 1 Dec 2020. (virtual oral presentation, published abstract).

Hudak, A, Bright, B, Rowell, E, Robertson, K, Pokswinski, S, Hiers, K, Prichard, S, Nowell, H, Holmes, C, Gargulinski, E and Soja, A. (2021) Estimating surface fuel density from TLS and

ALS: A two-tiered approach that accounts for sampling scale. Silvilaser 2021, 28-30 Sep 2021. (virtual oral presentation).

Hudak, AT, McCarley, R, Billmire, M, Miller, ME, French, N, Prichard, S, Saiki, C, Roberts, D, Stavros, N, Ottmar, R and Soja, A. (2020). Fuels and consumption estimated measured and modeled fuels at the Williams Flats Fire in Washington. American Geophysical Union Fall Meeting, 1-17 Dec 2020. (virtual oral presentation, published abstract).

Hudak, A, McCarley, R, Bright, B, Corrao, M, Ottmar, R, French, N and Soja, A. (2020) FASMEE Western Wildfire Campaign: Fuel consumption maps to reduce uncertainties in emissions. Third International Smoke Symposium, Raleigh, North Carolina, 20-23 Apr 2020. (virtual oral presentation, published abstract).

Hudak, A. (2019). A bottom-up, stakeholder-driven CMS for regional biomass carbon dynamics: Phase 2. Precision Forestry Cooperative Board Meeting, Seattle, Washington, 13 Dec 2019 (video presentation).

Hudak, A., Vogeler, J, Fekety, P, Filippelli, S. Kane, V, Kennedy, R, Babcock, C, Domke, G, Meddens, A, Mauro, F, Corrao, M, Halverson, K, and Bright, B. (2019). A bottom-up, stakeholder-driven CMS for regional biomass carbon dynamics: Phase 2. Carbon Monitoring Systems Science Team Meeting, La Jolla, California, 13-14 Nov 2019 (poster).

Hudak, AT, Fekety, P, Kane, V, Kennedy, R, Filippelli, S, Falkowski, M, Domke, G, Smith, A, Tinkham, W, Crookston, N, Corrao, M, Bright, B, Churchill, D, Kane, J, McGaughey, R, and Dong, J. (2019). Prototyping a methodology to develop regional-scale forest aboveground biomass carbon maps predicted from Landsat time series, trained from field and lidar data collections, and independently validated with FIA data. Carbon Monitoring Systems Science Team Meeting, La Jolla, California, 13-14 Nov 2019 (poster).

Hudak, A. (2019). A bottom-up, stakeholder-driven CMS for regional biomass carbon dynamics: Phase 2. Carbon Monitoring Systems Science Team Meeting, La Jolla, California, 13 Nov 2019 (oral presentation).

Hudak, A, McCarley, R, Fekety, P, Bright, B, Kato, A, Loudermilk, L, Rowell, E, Silva, C, Restaino, J, Prichard, S, Ottmar R and Weise, D. (2019). Quantifying biomass and biomass change at multiple scales from TLS and ALS. Invited seminar, Universiti Kebangsaan Malaysia, Kuala Lumpur, Malaysia, 1 Aug 2019. (oral presentation, published abstract).

Hudak, A, Kennedy, R, Fekety, P, Filippelli, S, Falkowski, M and Kane, V. (2019). Mapping forest aboveground biomass annually (2000-2016) from Landsat time series. Keynote for 6th International Conference on Space Science and Communication, Johor Bahru, Malaysia, 29 Jul 2019. (oral presentation, published abstract).

Hudak, A, McCarley, R, Restaino, J, Ottmar, R, Goulden, T, Volkamer, R and Fischer, E. 2019. Fuel consumption and emissions on the five WE-CAN/BB-FLUX wildfires selected for field and airborne LiDAR measurements. Western Wildfire Smoke Workshop, Boulder, Colorado, 23-25 Apr 2019. (oral presentation).

Hudak, A, Fekety, P, Filippelli, S, Falkowski, M, Kennedy, R, Kane, V, Domke, G, Crookston, N and Smith, A. (2019). Monitoring current and future forest carbon stores in the northwestern USA from Landsat time series, airborne lidar, and inventory plot data. Invited seminar, Barbara Wheatland Seminar Series, University of Maine, Orono, Maine, 13 Mar 2019. (oral presentation, published abstract).

Hudak, AT, Kato, A, Bright, B, Loudermilk, L, Hawley, C, Rowell, E, Hayakawa, Y, Axe, T, Moskal, M and Batchelor, J. (2018). Estimating fuel consumption from pre- and post-fire fuel measurements. Workshop on using lidar to improve fuel characterization for fire models. Los Alamos, New Mexico, 5 Nov 2018. (webinar).

Hudak, AT, Batchelor, J, Kato, A, Bright, B, Axe, T and Moskal, M. (2018). Drones for fire and fuels. University of Idaho Drone Summit, Moscow, Idaho, 1 Nov 2018. (oral presentation).

Hudak, AT. (2018). Making best use of commercially available airborne lidar surveys for regional forest and fuels management. Keynote for Remote Sensing for Forest Practitioners Conference, Edmonton, Alberta, Canada, 25 Oct 2018. (oral presentation, published abstract).

Kille, N, Volkamer, RM, Zarzana, KJ, Rowe, JR Alvarez, R, Nutter, C, Knote, TL, Campos, L, Oolman, DM, Plummer, M, Deng, Z, Wang, R, Ahmadov, M, Bela, SA, McKeen, CC, Schmidt, RB, Pierce, B, Hass, T, Goulden, J, . Restaino, J, Hudak, AT and Ottmar, RD. (2020) Quantifying the relationship between CO mass fluxes and satellite fire radiative power from wildfires. American Geophysical Union Fall Meeting, 1-17 Dec 2020. (virtual oral presentation, published abstract).

Kobziar, LN, Pingree, M, Watts, AC, Nelson, KN, Vuono, D, Moore, R, Smith, J, Dreaden, T, and Rideout, M. (2019). Accessing the life of smoke: using unmanned aircraft systems (sUAS) to sample viable microorganisms and environmental covariates during wildland fires. Presentation, 8th International Fire Ecology and Management Congress, 18-22 November 2019, Tucson, AZ.

Kobziar, LN, Vuono, D, Kohn, RA, Christner, B and Watts, AC. (2019) The life of smoke: how wildland fire aerosolizes viable microbial communities with atmospheric and terrestrial ramifications. Presentation, American Geophysical Union Fall meeting, 9-13 December 2019, San Francisco, CA.

Kobziar, LN, Vuono, D, Moore, R, Christner, B, Watts, AC, Gullett, B, Aurell, J, Kochanski, A, Betancourt, D and Dean, T. (2020) Microbial emissions affect biodiversity and ice nucleation potential in FASMEE smoke plumes. Presentation, 3rd International Smoke Symposium, 22 April 2020, Raleigh, NC.

Kobziar, L, Vuono, D, Moore, R, Dean, T, Betancourt, D, Watts, A, Christner, B, Aurell, J, Gullett, B, Kochanski, A and Tohidi, A. (2021) High-intensity Forest Fires Emit High Concentrations of Diverse, Viable, and Ice-Nucleating Bioaerosols. Presentation, American Association of Atmospheric Research 39th Annual Conference, 18-22 October 2021, Albuquerque, NM.

Loudermilk, L, Hudak, A, Flanagan, A, Goodrick, S, O'Brien, J and Hiers, K. (2020). Coarse-scale 3D fuel mapping for operational use in next-generation fire-atmosphere fire behavior models. USFS-NASA Joint Applications Workshop Virtual Pitchfest, 2-3 Jun 2020. (virtual oral presentation, published abstract).

McCarley, TR, Hudak, AT, Sparks, AM, Boschetti, L and Meddens, AJ. (2018). Quantifying fuel consumption for two western U.S. fires using repeat LiDAR. American Geophysical Union Fall Meeting, Washington, DC, 10-14 Dec 2018. (oral presentation, published abstract).

McCarley, TR., Hudak, AT and Bright, BC. (2018). Fishlake LiDAR. LiDAR-based forest inventory meeting with Fishlake National Forest managers, Richfield, Utah, 17 Apr 2018. (oral presentation).

McCarley, TR and Hudak, AT (2019). Quantifying interactions between wildfire, prior mountain beetle outbreak and harvest on forest aboveground biomass from bi-temporal lidar. 8th International Association for Fire Ecology Congress, Tucson, Arizona, 18-22 Nov 2019. (oral presentation, published abstract).

McCarley, R, Hudak, AT, Restaino, J, Ottmar, RD, Hass, B, Goulden, T, and Volkamer, RM. (2020) A Comparison of multi-temporal airborne laser scanning and the Fuel Characteristics Classification System for estimating fuel load and consumption. American Geophysical Union Fall Meeting, 1-17 Dec 2020. (virtual oral presentation, published abstract).

Nelson, KN, Watts, AC, Samburova, V, Khlystov, AY, Bhattarai, C, Moosmüller, H, Wilcox, EM and Giordano, M. (2018). An emissions sampling payload for use with small Unmanned Aircraft Systems (sUAS). Poster, International Society for Atmospheric Research using Remotely-piloted Aircraft, 9-12 July 2018, Boulder, CO.

Nelson, K, Watts, A, Boehmler, J, Samburova, V, Khlystov, A, Moosmüller, H, and Wilcox, E. (2019) Development of a compact, portable smoke emissions sampling instrument appropriate for use with small unmanned aircraft systems. 6th International Fire Behavior and Fuels Conference, 29 April-3 May 2019, Albuquerque, NM.

Nowell, H, Holmes, CD, Soja, AJ, Gargulinski, EM, Robertson, K, Hiers, JK, Wiggins, EB, Fite, C, McCarty, JL, Hudak, AT, Diskin, GS and Blake, DR. (2020) Fuel and emissions in a prescribed fire in the Blackwater River State Forest during FIREX-AQ: synthesis of observations from ground, aircraft, and satellites and comparison with models. American Geophysical Union Fall Meeting, 1-17 Dec 2020. (virtual oral presentation, published abstract).

Ottmar, R. (2015). Fire and Smoke Model Evaluation Experiment FASMEE), 5th International Fire Behavior and Fuels Conference, April 11-15, 2015. Portland, OR Ottmar, Roger. 2018. Fire and Smoke Model Evaluation Experiment western wildfire campaign, The Fire Continuum Conference, May 21-24, 2018, Missoula, MT.

Ottmar, R. (2016). Overview of Fire and Smoke Model Evaluation Experiment (FASMEE), 2nd International Smoke Symposium, November 14-17, 2016. Long Beach, CA

Ottmar, R. (2018). Fire and Smoke Model Evaluation Experiment, 2nd International Smoke Symposium, Long Beach, CA. (virtual oral presentation, published abstract).

Ottmar, R. (2018). FASMEE Collaboration with FIREX-AQ for Selection and Source Characterization during Western Wildfire and Rx Field Campaigns. FIREX-AQ Science Meeting, October 24-26, 2018, Boulder, CO

Ottmar, R., Brown, T, French, N, Larkin, N, Prichard, S, Watts, A, Hudak, A, Dickinson, M, Clements, C, Potter, B, Urbanski, S, Kochanski, A, Linn, R, Mell, R, Liu, Y and Baker, K (2018) The Fire and Smoke Model Evaluation Experiment Western Wildfire Campaign. AFE/IAWF Fire Continuum Conference, Missoula, Montana, 21-24 May 2018. (oral presentation, published abstract).

Ottmar, R., Larkin, S., Varner, M, Brown, T, French, N, Hiers, K, Hudak, A, Dickinson, M, Clements, C, Urbanski, S, Mell, R, Liu, Y, Kochanski, A and Baker, K. (2019). Fire and Smoke Model Evaluation Experiment (FASMEE): Collaboration with WE-CAN, BB-FLUX, and FIREX-AQ for selection and source characterization during western wildfire and Rx field campaigns. Western Wildfire Smoke Workshop, Boulder, Colorado, 23-25 Apr 2019. (oral presentation).

Ottmar, R., S. Larkin, T. Brown, N. French, K. Hiers, A. Hudak, B. Butler, M. Dickinson, C. Clements, A. Watts, M. Varner and A. Kochanski. Fire And Smoke Model Evaluation Experiment (FASMEE): a large integrated multiagency fire study. Third International Smoke Symposium, Raleigh, North Carolina, 20-23 Apr 2020. (virtual oral presentation, published abstract). Ottmar, R., S. Larkin, M. Varner, T. Brown, N. French, K. Hiers, A. Hudak, M. Dickinson, C. Clements, S. Urbanski, R. Mell, Y. Liu, A. Kochanski and K. Baker. Fire and Smoke Model Evaluation Experiment (FASMEE): Collaboration with WE-CAN, BB-FLUX, and FIREX-AQ for selection and source characterization during western wildfire and Rx field campaigns. Western Wildfire Smoke Workshop, Boulder, Colorado, 23-25 Apr 2019. (oral presentation).

Ottmar, RD. 2020. The Fire and Smoke Model Evaluation Experiment (FASMEE)- An Overview of the Project. Third International Smoke Symposium, Raleigh, North Carolina, 20-23 Apr 2020. (virtual oral presentation, published abstract).

Ottmar, R, Cronan, J, Hudak, A, Van Winkle, B and Prichard, S. (2020) FASMEE – characterizing the source for fuel and fuel consumption. Third International Smoke Symposium, Raleigh, North Carolina, 20-23 Apr 2020. (virtual oral presentation, published abstract).

Ottmar, RD. (2020) Western Wildfires and Southwest Campaign: Characterizing the source for fuels, fuel consumption, and total smoke. 3rd International Smoke Symposium, Raleigh, NC. Third International Smoke Symposium, Raleigh, North Carolina, 20-23 Apr 2020. (virtual oral presentation, published abstract).

Ottmar, RD. 2015-2021. Presented FASMEE at 30 Rx410 (Smoke Management) classes from 2015-2021.

Prichard, S, Ottmar, R, Hudak, R, Kennedy, M, Parsons, R, Rowell, E, Silva, C, Skowronski, N, Batchelor, J, Bester, M and Cova, G. (2020) 3D fuel characterization for evaluating physics-based fire behavior, fire effects, and smoke models on US Department of Defense military lands. SERDP-ESTCP Symposium, 1 Dec 2020. (virtual poster, published abstract).

Restaino, J, Ottmar, R and Hudak, A. (2019) Pre- and post-fire characterization of fuels at prescribed burns in longleaf pine stands in the southeastern United States. 6th International Fire Behavior and Fuels Conference, Albuquerque, New Mexico, 29 Apr – 3 May 2019. (oral presentation, published abstract).

Saiki, CM, Stavros, EN, Roberts, DA, Hudak, AT, French, NH and Kalashnikova, OV. (2020) Mapping heterogeneous fuel characteristics and fuel consumption using AVIRIS, LiDAR, and field data for fire emissions modeling. American Geophysical Union Fall Meeting, 1-17 Dec 2020. (virtual oral presentation, published abstract).

Soja, AJ, Hudak, AT, McCarty, JL and Hiers, JK. (2018) FIREX-AQ: Fueled from below: linking fire, fuels and weather to atmospheric chemistry. AFE/IAWF Fire Continuum Conference, Missoula, Montana, 21-24 May 2018. (oral presentation, published abstract).

Soja, A, Gargulinski, E, Wiggins, E, McCarty, J, French, N, Hudak, A, Li, L, Trujillo, C, Thapa, L, Turney, F, Rintsch, E, Yokelson, B, Kubota, S, Fite, C, Agastra, A, Saide, P, Berman, M and Hiers, K. (2020) Fueled from below: Linking fire, fuels, and weather to atmospheric chemistry. FIREX-AQ Science Team meeting, 11 Jun 2020.

Soja, A, Gargulinski, E, Wiggins, E, McCarty, J, Hudak, A, Rintsch, E, Hier K, Schmidt, C and Fain, J. (2020) Fueled from below: linking fire, fuels, and weather to atmospheric chemistry. Third International Smoke Symposium, Raleigh, North Carolina, 20-23 Apr 2020. (virtual oral presentation, published abstract).

Soja, AJ, Gargulinski, E, Wiggins, EB, Kondagunta, S, McCarty, JL, Hudak, AT, Hiers, K, Xu, C, Zhou, M and Wang, J. (2020) FIREXAQ: Insights into satellite- and fuel-based fire emissions. American Geophysical Union Fall Meeting, 1-17 Dec 2020. (virtual oral presentation, published abstract).

Soja, A, Gargulinski, E, Wiggins, E, McCarty, J, French, N, Hudak, A, Li, A, Trujillo, C, Thapa, L, Turney, F, Rintsch, E, Yokelson, B, Kubota, S, Fite, C, Agastra, A, Saide, P, Berman, M and Hiers, K. Fueled from below: Linking fire, fuels, and weather to atmospheric chemistry. FIREX-AQ Science Team meeting, 11 Jun 2020.

Soja, A, Gargulinski, E, Wiggins, E, McCarty, J, Hudak, A, Rintsch, E, Hiers, K, Schmidt, C and Fain, J. Fueled from below: linking fire, fuels, and weather to atmospheric chemistry. Third International Smoke Symposium, Raleigh, North Carolina, 20-23 Apr 2020. (virtual oral presentation, published abstract).

Soja, A, Gargulinski, E, Wiggins, E, McCarty, J, Hudak, A, Hiers, K, French, N, Yokelson, B, Kubota,S, Pierce, B, Crawford, J, Warneke, C, Dibb J and Schwartz, S. (2021) Fire Influence

on Regional to Global Environments and Air Quality (FIREX-AQ). Tactical Fire Remote Sensing Advisory Committee Meeting, 11 May 2021. (virtual oral presentation).

Toolan, MJ, Kreye, JK, Shearman, TM, Varner, M and Cronan, J. (2021) Quaking aspen regeneration following high severity prescribed burns in the mountains of central Utah. Oral presentation at the 9th International Fire Congress, Destin, FL. November 30-December 4, 2021.

Varner, JM, Kobziar, LN, Hudak, AT, Ottmar, RD, Watts, AC, Kreye, JK, Shearman, T and O'Brien, JJ. (2019)Big idea fire effects research in large experimental fires: balancing challenges with opportunities. Presentation, 8th International Fire Ecology and Management Congress, 18-22 November 2019, Tucson, AZ.

Varner, JM. 2018-2021. Presented FASMEE and Fire Effects at several Rx training classes from 2018-2021.

Velez, AK, Coates, TA, and Watts, AC. The controlled aspect of wildland fire: a multifaceted examination of factors influencing prescribed burns in the US. Invited webinar, EPA Social Environmental Science Exchange, 18 November 2020 (online).

Volkamer, RM, Kille, N, Lee, C, Zarzana, KJ, Koenig, TK, Howard, B, Nutter, R, Knote, C, Campos, TL, Plummer, DM, Oolman, L, Deng, M, Wang, Z, Ahmadov, R, Pierce, RB, Zahn, A, Obersteiner, F, Goulden, T, Hass, B, Fischer, EV, Hudak, AT, Restaino, J, and Ottmar, RD. 2019. [The BB-FLUX project: How much fuel goes up in smoke?] American Geophysical Union Annual Meeting, San Francisco, California, 9-13 Dec 2019. (oral presentation, published abstract).

Volkamer, R, Kille, N, Zarzana, K, Ahmadov, R, Bela, M, McKeen, S, Haas, B, Goulden, T, Hudak, A, and Ottmar, R. BB-FLUX collaboration with NEON/FASMEE. Western Wildfire Smoke Workshop, Boulder, Colorado, 23-25 Apr 2019. (oral presentation).

Volkamer, RM, Kille, N, Lee, C, Zarzana, KJ, Koenig, TK, Howard, B, Nutter, R, Knote, C, Campos, TL, Plummer, DM, Oolman, L, Deng, M, Wang, Z, Ahmadov, R, Pierce, RB, Zahn, A, Obersteiner, F, Goulden, T, Hass, B, Fischer, EV, Hudak, AT, Restaino, J, and Ottmar, RD. The BB-FLUX project: How much fuel goes up in smoke? American Geophysical Union Annual Meeting, San Francisco, California, 9-13 Dec 2019. (oral presentation, published abstract).

Watts, AC. Unmanned Aircraft Systems (UAS) for FASMEE and the Rx Fire Science Consortium. Invited Presentation, FASMEE/Rx Fire Science Consortium Workshop, 14 August 2018, Pacific Wildland Fire Sciences Laboratory, Seattle, WA.

Watts, AC. Academic leadership panel on UAS. 21st unmanned aircraft systems. Technical Analysis and Applications Center meeting, 10-12 December 2019, New Mexico State University, Las Cruces, NM.

Watts, AC. Operational use of unmanned aircraft over wildland fires: recent UAS work at the Desert Research Institute and the Fire and Smoke Model Evaluation Experiment. Invited presentation, Pacific Northwest National Laboratory. 15 July 2019, Richland, WA.

Watts, AC. UAS Planning for the Fire and smoke model evaluation experiment (FASMEE). Invited presentation, NASA/U.S. Forest Service Tactical Fire Remote Sensing Advisory Committee Spring Meeting, 29 May 2019, Mountain View, CA.

Watts, AC. Small unmanned aircraft systems use in wildland fire research and management. Invited Presentation, 6th International Fire Behavior and Fuels Conference, 29 April-3 May 2019, Albuquerque, NM.

Watts, AC, Samburova, V, Moosmüller, H, Khlystov, A, Sengupta, D, and Bhatterai. C. Selecting important fuels for biomass emissions research. Presentation, 8th International Fire Ecology and Management Congress, 18-22 November 2019, Tucson, AZ.

Watts, AC, Ottmar, R, Grimm, D, Juchzter, J, Melarkey, P, Page, D, Kobziar, LN, Nelson, KN, and Boehmler, J. Unmanned aircraft systems (UAS) for data collection at the Fire and Smoke Model Evaluation Experiment (FASMEE). Presentation, 8th International Fire Ecology and Management Congress, 18-22 November 2019, Tucson, AZ.

Watts, AC Environmental effects of wildfires, and areas of current and future concern. Invited presentation, Nevada Legislature Interim Committee on Wildfires. 2 June 2020, Carson City, NV.

Watts, AC, Ottmar, RD, Gullett, B, Kobziar, LN, Aurell, J, Grimm, D, Hiers, K and Holder, A. Wildland Fire Emissions and Atmospheric Measurements from Unmanned Aircraft Systems to support FASMEE. Presentation, 3rd International Smoke Symposium, 22 April 2020, Raleigh, NC.

Watts, AC Applications of unmanned aircraft for wildland fire research and monitoring. Invited Seminar, University of Illinois at Chicago School of Engineering, 28 February 2020, Chicago, IL.

Watts, AC. Wildfire Hazards Research and Mitigation. Presentation to U.S. Congressman Mark Amodei, 20 February 2020, Desert Research Institute, Reno, NV.

Watts, AC, Mell, W, Ottmar, RD, Bova, A, Kochanski, A, Cornwall, K and McDuffey, J. 2021. Collaborative manager-modeler planning to support future prescribed fires at Fishlake National Forest, Utah. Workshop, 19-20 October 2021, Richfield, UT.

8. Data Products—FASMEE Western Wildfire Campaign

Fekety, PA and Hudak, AT. (2020) LiDAR-derived forest aboveground biomass maps, northwestern USA, 2002-2016. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1766

Filippelli, S.K., Falkowski, MJ, Hudak, AT and Fekety, PA. (2020) CMS: Pinyon-juniper forest live aboveground biomass, Great Basin, USA, 2000-2016. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1755

Fekety, P.A. and Hudak, AT. (2019) Annual aboveground biomass maps for forests in the northwestern USA, 2000-2016. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1719

Restaino, J. and Ottmar, R. (2019). Source characterization of wildfires flown by WECAN and BB-FLUX in 2018. Forest Service Box. https://usfs.app.box.com/folder/53606703794?s=3q23chey3qj79mh2e7u096b351ypd7ub

Note: As analyses are active and ongoing, neither datasets nor metadata specific to the WWC fires have yet been prepared. When they are, they will be modeled after the McCarley et al. (2018) dataset archived on the FS Research Data Archive; these data supported the McCarley et al. (2020) paper cited above.

McCarley, T.R., Kolden, CA, Vaillant, NM, Hudak, AT, Smith, AMS, Wing, BM, Kellogg BS and Kreitler, J. (2018) LiDAR and Landsat change indices for the 2012 Pole Creek Fire. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2018-0017

Note: It is likely that the WWC datasets will be archived instead, or in addition, on the WIFIRE Commons based at the San Diego Supercomputing Center (https://wifire-data.sdsc.edu/), where we expect that supercomputing resources will facilitate greater discovery and use for fire and smoke modeling. There, we have archived maps of 6 fuel attributes (aboveground biomass, downed wood biomass, canopy fuel load, canopy height, canopy base height, canopy bulk density) predicted from FIA plot data and lidar collected over a large portion of OR. These maps can be considered prototypes of fuel maps we intend to produce where lidar data are available across the western US.

Mauro, F, Hudak, AT, Fekety, PA, Frank, B, Hailemariam, T, Bell, DM, Gregory MJ and McCarley, TR.Lidar derived above ground biomass (AGB) for 20 lidar acquisitions in Oregon. WIFIRE Commons. Available at https://wifire-data.sdsc.edu/dataset/above-ground-biomass-agb.

Mauro, F, Hudak, AT, Fekety, PA, Frank, B, Hailemariam, T, Bell, DM, Gregory MJ and McCarley, TR. (2021). Downed wood biomass (DWB) for 20 lidar acquisitions in Oregon. WIFIRE Commons. Available at https://wifire-data.sdsc.edu/dataset/downed-wood-biomass-dwb.

Mauro, F, Hudak, AT, Fekety, PA, Frank, B, Hailemariam, T, Bell, DM, Gregory MJ and McCarley, TR. (2021). Canopy height (CH) for 20 lidar acquisitions in Oregon. WIFIRE Commons. Available at https://wifire-data.sdsc.edu/dataset/canopy-height-ch.

Mauro, F, Hudak, AT, Fekety, PA, Frank, B, Hailemariam, T, Bell, DM, Gregory MJ and McCarley, TR. (2021). Canopy base height (CBH) for 20 lidar acquisitions in Oregon. WIFIRE Commons. Available at https://wifire-data.sdsc.edu/dataset/canopy-base-height-cbh.

Mauro, F, Hudak, AT, Fekety, PA, Frank, B, Hailemariam, T, Bell, DM, Gregory MJ and McCarley, TR. (2021). Canopy bulk density (CBD) for 20 lidar acquisitions in Oregon. WIFIRE Commons. Available at https://wifire-data.sdsc.edu/dataset/canopy-bulk-density-cbd.

Mauro, F, Hudak, AT, Fekety, PA, Frank, B, Hailemariam, T, Bell, DM, Gregory MJ and McCarley, TR. (2021). Canopy fuel load (CFL) for 20 lidar acquisitions in Oregon. WIFIRE Commons. Available at https://wifire-data.sdsc.edu/dataset/canopy-fuel-load-cfl.

9. Data Products—FASMEE Southwestern Campaign

Data is still being compiled, reduced and analyzed for the FASMEE SW campaign. Once complete, all project data will be stored in the Forest Service Data Archive upon publication of study results. JFSP will be notified upon upload and availability.

10. Media:

Science Mag: https://www.sciencemag.org/news/2020/09/covid-19-worries-douse-plans-fire-experiments

US Forest Service: https://www.fs.usda.gov/rmrs/projects/fire-and-smoke-model-evaluation-experiment-fasmee-fishlake-national-forest-prescribed-burn

https://www.fs.usda.gov/rmrs/science-spotlights/using-%E2%80%9Cgood%E2%80%9D-fires-reduce-%E2%80%9Cbad%E2%80%9D-fire-effects-and-smoke-impacts

https://www.fs.usda.gov/pnw/pnw-research-highlights/fire-and-smoke-evaluation-experiment-fasmee

Federal Laboratory Consortium Calendar: https://federallabs.org/media/publication-library/2020-flc-planner?hss_channel=fbp-122806387764640

The Atlantic: https://www.theatlantic.com/science/archive/2019/10/why-scientists-are-setting-wildfires-purpose/600550/

Weather Channel: https://weather.com/news/weather/video/the-us-forest-service-torches-2000-acres-of-utah-for-science?isSubsequent=true

Science Focus: https://www.sciencefocus.com/planet-earth/wildfire-science-computer-models-drones-and-laser-scanning-help-fan-the-flames-and-prevent-widespread-devastation/

NASA: https://www.nasa.gov/feature/goddard/2019/fire-forecasting-from-smart-phone-in-wilderness

Science Focus: https://www.sciencefocus.com/planet-earth/wildfire-science-computer-models-drones-and-laser-scanning-help-fan-the-flames-and-prevent-widespread-devastation/

Wildfire Today:
https://wildfiretoday.com/2019/09/13/update-on-the-fire-and-smoke-model-evaluation-experiment/

FireScience.gov Friday Flash:
https://us2.campaign-archive.com/?u=5f6de7b069a57255f980944b4&id=11b978e7d6

Samantha Wohlfeil: 6/24/2021. Inlander. "What if a brand new field of science could explain how wildfire smoke carries microbes?" https://www.inlander.com/spokane/what-if-a-brand-new-field-of-science-could-explain-how-wildfire-smoke-carries-microbes/Content?oid=21895316

Scott Jackson. 6/30/2021. Moscow-Pullman Daily News. "The 'heat dome': what it is and what could happen if we continue to see more" https://dnews.com/local/the-heat-dome-what-it-is-and-what-could-happen-if-we-continue-to-see/article_a85f48aa-c8b1-5012-a637-48d7c5850512.html

Leslie Young. 6/5/2021. Global News. "The particles, gases and organisms in wildfire smoke — and what they mean for your health" https://globalnews.ca/news/7919844/wildfire-smoke-health-effects/

Leigh Cooper: Vandal Theory Podcast 5/11/2021. "The Vandal Theory: Episode 8: Microbes in Smoke" podcast. Uidaho.edu/vandaltheory

Megan Sever. Science News 4/13/2021 Wildfires launch microbes into the air: How big of a health risk is that? www.sciencenews.org/article/wildfire-smoke-microbes-air-health-risk-bacteria-fungi

Joseph Serna, Los Angeles Times 2/1/2021. https://www.latimes.com/california/story/2021-02-01/wildfire-smoke-microbes-in-the-air

Meagan Cantwell, Science Podcasts, AAAS. 1/1/2021. https://www.sciencemag.org/podcast/areas-watch-2021-and-living-microbes-wildfire-smoke

Joanne Lu, NPR Podcast Goats and Soda:
https://www.npr.org/sections/goatsandsoda/2020/12/23/948157452/we-all-know-smoke-is-bad-for-your-health-it-could-be-worse-than-you-think

Jordan Rane, Columbia Insights, February 2021. https://columbiainsight.org/smoke-is-alive/

Shayla Love, Vice News, January 2021. https://www.vice.com/en/article/jgqazy/wildfire-smoke-is-alive

Eamon Dreisbach. 12/29/2020. Healio.com "Q&A: Wildfire smoke may carry bacteria, fungi" https://www.healio.com/news/infectious-disease/20201229/qa-wildfire-smoke-may-carry-bacteria-fungi

Dangers of wildfire smoke spreading infections (Global) - BBC News - Dec. 18, 2020 https://www.youtube.com/watch?v=dbm9J5-egSc

Matt McGrath, BBC News (online): 18 December 2020. Wildfire Smoke May Spread Infectious Disease. https://www.bbc.co.uk/news/science-environment-55350185

Matt Simon, WIRED Magazine: 17th December, 2020. https://www.ncbi.nlm.nih.gov/search/research-news/12267/

MotherJones: https://www.motherjones.com/politics/2020/12/wildfire-smoke-is-loaded-with-microbes-is-that-dangerous/

David Grossman, Inverse: 18th December 2020. https://www.inverse.com/science/how-bad-is-smoke-really

Travis Bubenik, Courthouse News, December 2020: https://www.courthousenews.com/researchers-say-infectious-microbes-could-be-lurking-in-wildfire-smoke/

Leman, J. 2019. Popular Mechanics. “How This Researcher Invented an Entirely New—and Entirely Badass—Field of Science” Dec.20,2019. https://www.popularmechanics.com/science/environment/a30246543/pyroaerobiology-smoke-signals-interview/

Leman, J. 2019. Nature, Nature-Asia, “Wildfires spark population booms in fungi and bacteria populations”. Jan 16 Jan. 16 2019. Article with Kobziar interview: https://www.nature.com/articles/d41586-019-00151-8

Waldman, Ariel. 2020. “Microbes living in wildfire smoke”. Episode on pyroaerobiology. https://www.youtube.com/watch?v=FrkWqIEW-U4; April 2020.

11. USFS Websites

18 Aug 2016. “Mapping aboveground biomass annually across the northwestern USA from LiDAR and Landsat image time series” summarizing how we developed a prototype Carbon Monitoring System from assembled field plot and lidar datasets that can transfer forest biomass estimates to unsampled locations across space and time. https://www.fs.usda.gov/rmrs/science-spotlights/got-biomass-questions-there%E2%80%99s-map

20 Jul 2017. “Rethinking how we measure forest fuels for advancing wildland fire science and management” 2018 Research Highlight summarizing cutting-edge techniques to measure fuels in 3-dimensions as inputs to physical fire behavior models, to advance understanding of fuel controls on fire behavior in frequently burned southern pine forest ecosystems. https://www.fs.fed.us/research/highlights/highlights_display.php?in_high_id=1524

3 Jul 2019. “Fire and Smoke Model Evaluation Experiment (FASMEE): Fishlake National Forest prescribed burn” summarizing a large-scale interagency effort to identify how fuels, fire behavior, fire energy and meteorology interact to determine the dynamics of smoke plumes, the long-range transport of smoke and local fire effects such as soil heating and vegetative response. https://www.fs.usda.gov/rmrs/projects/fire-and-smoke-model-evaluation-experiment-fasmee-fishlake-national-forest-prescribed-burn

29 Aug 2019. "Using "good" fires to reduce "bad" fire effects and smoke impacts" Science Spotlight summarizing that "Good" fire vs "bad" fire should not be equated with prescribed fire vs wildfire, but on whether desired fire effects are achieved that meet forest and fuels management goals. https://www.fs.usda.gov/rmrs/science-spotlights/using-%E2%80%9Cgood%E2%80%9D-fires-reduce-%E2%80%9Cbad%E2%80%9D-fire-effects-and-smoke-impacts

8 May 2020. "Where's the biomass? A new approach for quantifying biomass and carbon in the Western United States" summarizing how a prototype Carbon Monitoring System that I designed draws upon the power of computer modeling, LiDAR, field data, and aerial photography to map forest and woodland biomass across the Pacific Northwest, Inland Northwest, and Great Basin regions. https://www.fs.usda.gov/rmrs/science-spotlights/got-biomass-questions-there%E2%80%99s-map

Appendix C—Budget Summary for Phase 2 and Additional Work

The Joint Fire Science Program (JFSP) and the Environmental Security Technology Certification Program (ESTCP) initiated the Fire and Smoke Model Experiment (FASMEE) (https://fasmee.net) by funding JFSP Project 15-S-01-01. Phase 1was completed and further funding of $763,685 was received from the JFSP in 2018 to initiate data collection for the western wildfire and the southwest campaigns. The JFSP funds were used as leverage to bring in-kind support from the FIREX-AQ program sponsored by NOAA and NASA. Furthermore, the funding was used to secure an additional $1,495,000 from the US Forest Service PNW Research Station, US Forest Service Washington Office Fire and Aviation Management, and EPA. The cooperation and funding resulted in 30 additional publications, 50 presentations and the sharing of fuels, fire behavior, energy, plume, and smoke data.

JFSP funds for FASMEE Phase 2-data collection		
JFSP Funding	**$**	**763,685.00**
Other Funding_US Forest Service_EPA	**$**	**1,495,000.00**
Total FASMEE Phase 2	**$**	**2,258,685.00**

JFSP funds for FASMEE Phase 2-data collection		
FASMEE_Additional Work_Ottmar_2017_401K		**Funds**
	$	400,525.00
U of W	$	161,254.00
PNWRS Overhead	$	20,475.00
Mich Tech (Nancy French)	$	36,000.00
DRI (Tim Brown)	$	27,000.00
RMRS(Hudak)	$	126,265.00
Tall Timbers (Hiers)	$	30,006.00
Subtotal	**$**	**401,000.00**
JFSP_FASMEE_Additional Work_Ottmar_2018_94K	**$**	**94,142.00**
U of W	$	43,248.00
RMRS (Hudak)	$	37,318.00
PNWRS Overhead	$	13,576.00
Subtotal	**$**	**94,142.00**
JFSP_FASMEE_Additional Work_Ottmar_2019_32K	**$**	**32,240.00**
PNWRS_Ta_labor	$	2,240.00
RMRS_Hudak_Aviation Dynamics	$	30,000.00
Subtotal	**$**	**32,240.00**
JFSP_FASMEE_Additional Work_Ottmar_2019_236K	**$**	**236,303.00**
PNWRS and RMRS_Hudak	$	111,000.00
DRI_Watts	$	45,000.00
SJSU_Clements	$	40,909.00
U of W_Varner	$	39,394.00
Subtotal	**$**	**236,303.00**

Other funds for FASMEE Phase 2-data collection		
FASMEE_Received from EPA_FASMEE_2018	$	45,000.00
DRI_Watts	$	37,500.00
PNWRS Overhead	$	7,500.00
Subtotal	**$**	**45,000.00**
FASMEE_Received from PNW Research Station_Ottmar_2018_700K	$	700,000.00
U of Washington	$	260,000.00
Tall Timbers	$	50,000.00
U of Utah	$	35,000.00
SJSU	$	60,000.00
RMRS	$	145,000.00
NRS	$	75,000.00
SRS	$	60,000.00
PNWRS Overhead	$	15,000.00
Subtotal	**$**	**700,000.00**
FASMEE_Received from PNW Research Station_Ottmar_2018_400K	$	400,000.00
University of Washington	$	400,000.00
Subtotal	**$**	**400,000.00**
FASMEE__Received from PNW Research Station_ Ottmar_2019_250K	$	250,000.00
RMRS_Butler	$	50,000.00
DRI_Watts	$	40,000.00
TTRS	$	70,000.00
U of Utah_Kochanski	$	40,000.00
SJSU_Clements	$	20,000.00
PNWRS_FERA_Ottmar	$	10,000.00
PNWRS_Airfire_Larkin	$	20,000.00
Subtotal	**$**	**250,000.00**
FASMEE_Received from Washington Office Fire and Aviation Management_Ottmar_2019_100K	$	100,000.00
University of Washington	$	100,000.00
Subtotal	**$**	**100,000.00**