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Perspective

Embracing Complexity to Advance the Science of Wildland Fire Behavior

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Abstract: Wildland fire behavior research has largely focused on the steady-state interactions between fuels and heat fluxes. Contemporary research is revealing new questions outside the bounds of this simplified approach. Here, we explore the complex interactions taking place beyond steady-state assumptions through acknowledging the manufactured separation of research disciplines in fire science and the dynamic interactions that unfold when these separations are removed. Through a series of examples spanning at least four research disciplines and three ranges of spatial scale, we illustrate that by precisely defining parameters in a way that holds across scales and relaxing one steady-state simplification, we begin to capture the inherent variability that has largely eluded the fire behavior community. Through exploring examples of "deep interdependence," we make the case that fire behavior science is well equipped to launch forward into more complex lines of inquiry.

Keywords: complexity; combustion kinetics; energy flux; fire-atmosphere; flammability; heterogeneity; non-steady state; phase space

1. Introduction

The field of fire behavior science has traditionally taken a somewhat simplified approach in quantifying energetic interactions [1–5]. This simplified approach was borne out of a lack of adequate field data and a need to support firefighter planning and safety through rapid predictions. Such simplifications resulted in a profusion of research on the steady-state forward progression of a flaming front, subject to a constant driving surface wind in a neutral atmosphere for continuous surface fuels. This traditional approach to modeling fire behavior is embedded in numerous modern modeling tools (e.g., References [6–9]) used widely for both firefighter support and research.

Steady-state assumptions that focus on mean spread rate handicap attempts to understand the role of variability in complex systems. This variability arises, not only in the movement of the combustion zone, but also in dynamics of the involved natural systems [10,11]. Repercussions from a focus on mean spread rate can include a knowledge gap in understanding variability, the deviation of resources away from more complex interactions, and an overemphasis on the potentially erroneous role a small number of variables play in the majority of interactions.

There is widespread agreement that the steady-state fire spread paradigm is insufficient in addressing complex and changing fire environments or advancing fire behavior research [12,13]. What is less agreed upon is the path forward in addressing this complexity [14,15]. Exploring the opportunities to move away from a steady-state approach is the focus of this paper.

Steady-state fire behavior results from assuming that the complex exchange between seemingly separate research foci can be reduced to a few simple inputs (Figure 1a). For example, when considering the relationship between wind and wildfire, simplifying the interaction between wind fields and a flame to a single kinetic energy perturbation (at chest height) ignores the influence of changes in pressure around the entire flame envelope [16]. This simplification also ignores the influence of surface heating and the variable drag from vegetation (e.g., References [17,18]). This approach—including its assumptions and simplifications—leads to an erroneous logical conclusion that air movement above, below, and tangent to this forcing mechanism does not influence the energetic interactions of that flame. Beyond this, the simplified relationship between wind and wildfire places emphasis on the flame morphology above the combustion zone rather than within the regions where fuels and oxygen are mixing to produce the visible flame. We posit that by systematically acknowledging the interactions occurring among these previously isolated systems, a much deeper understanding of fire behavior will form (Figure 1b).

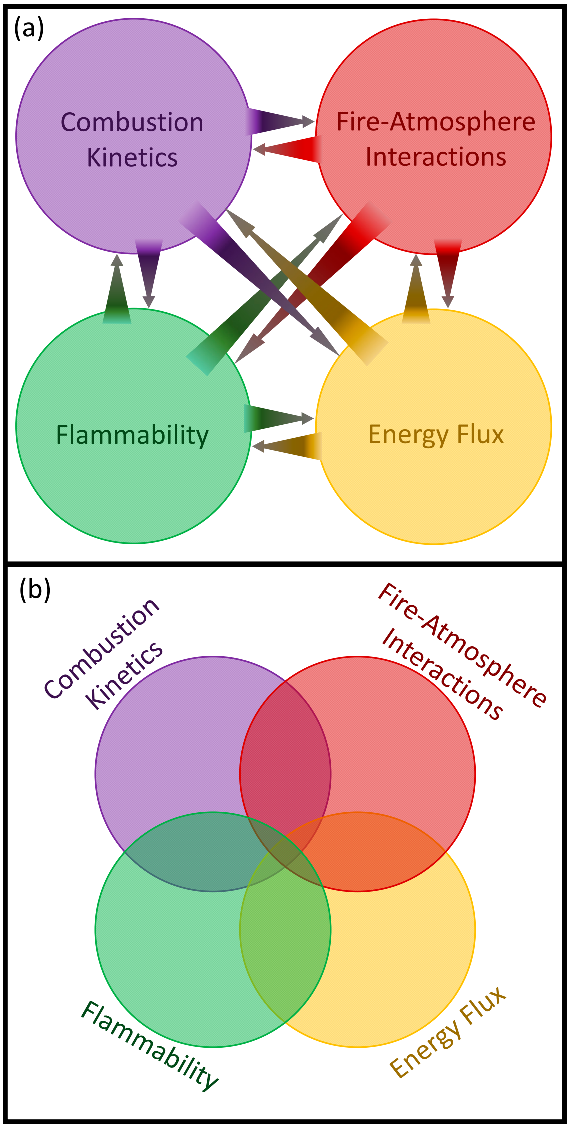

Figure 1. Exchange of information between areas of research. The top panel (**a**) diagrams the current structure used in distilling and coupling information between seemingly different fire research areas. The bottom panel (**b**) represents a transition to a more integrated approach where information is shared across fire research areas.

We explore four key research areas highlighting the need for a more complex and intersectional approach to fire behavior science. Complexity is introduced by relaxing assumptions and expanding objectives that bound the traditional system, thereby yielding a deeper understanding of the phenomena involved in wildland combustion dynamics. Specifically, we address potential deviations in the phase space of fire behavior through exchanges between the following research areas: Flammability, energy flux, fire-atmosphere interactions, and combustion kinetics (Figure 1).

2. Parameters and Definitions

Traditionally, fire behavior has been defined as a list of descriptors, such as rate of spread or fire-line intensity, often averaged over both space and time. One of the impediments to developing a careful approach with added complexity is this list-based definition. In order to discuss a wider breadth of science and shed limiting approaches, we start by defining fire behavior science as the study of energetic interactions within and among combustion zones and the surrounding natural systems. Likewise, in order to have a meaningful conversation about the complex interactions among the four research foci of interest (combustion kinetics, flammability, energy flux, and fire-atmosphere interactions), we must first carefully define each. We define combustion kinetics as the mixing and reaction rates associated with disassembling hydrocarbons during ignition, propagation, and extinction. Flammability, which is traditionally viewed simply as the ability of a fuel to burn [19], is broadened to discuss the physiological and environmental factors that influence the ability of a fuel or groups of fuels to combust [13]. Energy flux, which includes heat flux, is defined as the exchange of energy per unit area per unit time. However, energy flux not only includes the flame envelope and surrounding involved fuel, but also the exchange of energy without flame present. Lastly, fire-atmosphere interactions describe how momentum and energy fluxes from fire perturbs the atmosphere and vice versa [20,21].

3. Scales of Influence

The complexity in fire behavior science can be illustrated at the scale of an individual fuel particle, working through the scale of a prescribed fire, and ending with a fire complex. Our intention in addressing multiple spatial scales is to outline the complex interactions that may be influencing wildland fires across scales and the importance of scale-appropriate assumptions of parameters used. Thus, we do not repeat concepts at each scale, but leave it to the reader to draw those parallels. This is not meant to be an exhaustive list of scales of influence nor of parameters involved, but rather a discussion that provokes the reader to consider these and other complex interactions that characterize wildland fires.

3.1. Particle Scale

To explore the limitations of current approaches and possible new avenues, we examine a hypothetical study whose methods reflect the status quo in fire research. The objective of this study is to examine the heat exchange between a small mass of fuel, the ambient environment, and an approaching flaming front. The whole system is subject to a moderate wind. The following assumptions are made: The heat flux incident on the fuel is steady and portioned into known delivery mechanisms (convection, conduction, and radiation); moist pellets of cellulose represent the individual fuel particles; the ambient conditions are steady in both space and time, and with an excess of oxygen available in the ambient air.

Our hypothetical study approach is familiar to most fire behavior scientists and has resulted in a strong body of literature on steady-state flame propagation in a fuel (e.g., References [1,4,22–24]). However, if we loosen one assumption, we identify new lines of inquiry. Something as simple as acknowledging the boundary layer around individual particles or the proximity of particles to each other may have large impacts. The presence of a boundary layer results in a non-linear treatment of the local atmosphere as air and flames interact with unburned or burning particles. The proximity of two or more particles to each other further modifies the local flow characteristics around and through the system. When the flow is variable, this also means that the heat flux delivered during preheating and combustion varies [25,26]. With varying heat flux and air, the assumption that combustion kinetics are constant no longer holds [27] because preheating is now accompanied by convective cooling [26]. Likewise, the combustion zone is no longer receiving a constant and sufficient source of oxygen, but is rather experiencing a variable source driven by both the larger dominant flow and the physical and buoyant flow obstructions from the immediate surroundings [28]. As the experimental fuel particles are heated and become involved in the combustion process they change in chemical and structural makeup [29]. These changes further influence the immediate flow around both the particle and the entire fuel mass through inducing further variability in combustion kinetics, heat fluxes, localized momentum fluxes, and ventilation. Finally, if the study was conducted outdoors, allowing for exposure to dynamic solar radiation, the boundary layers of the fuel mass and individual particles would contribute dramatically to local moisture exchange [30].

3.2. Prescribed Fire Scale

Extending the hypothetical experiment to investigate fire behavior at the scale of a prescribed fire further reveals the weakness of a steady-state assumption. If the study aims to understand the flammability of a common native plant that dominates the fuels in a prescribed fire, it would likely involve the following traditional assumptions: Heat flux incident on an individual plant is constant; the neighboring plants and plant material do not influence flammability; the ambient conditions do not contribute to flammability, and there is an excess of oxygen available in the ambient air.

The hypothetical study follows a familiar approach, which reflects a large body of existing work on plant flammability (e.g., References [19,31,32]). We explore the results of removing the assumption that there is an excess of oxygen available in the ambient air.

Prescribed fires typically occur during marginal burning conditions [33]. In these environments, small-scale variation in local conditions as well as micro-scale atmospheric dynamics can have a disproportionate influence on combustion [34–36]. Rates of vegetation response to changes in ambient conditions (i.e., relative humidity, fuel moisture, air temperature) also affect combustion dynamics [13]. The abundance and arrangement of vegetation present around the study plant, as mentioned earlier, will influence ambient air flow as well as local moisture fluxes forced by intermittent solar heating.

During a prescribed burn scenario, one might expect light to moderate winds and a regionally unstable atmosphere that would facilitate smoke dispersion [37]. However, this may not be the case around each study plant since the presence/absence of a canopy may alter the local stability through variability in solar heating and the density of accompanying vegetation may produce significant drag/damping of local winds. The strong potential for damping of the flow of air to the study plant could result in variability of local combustion kinetics due to variable delivery of oxygen to portions of the study area. Thus, we have a plausible scenario where the ventilation of the combustion zone is dependent upon the structure of the surrounding vegetation matrix.

With an oscillating oxygen source comes a similar oscillation in heat flux to the study plant. This pulsating behavior would produce rapid convective fluxes due to potential flame contact and cooling as ambient air is drawn into and around the combustion zone [38]. Such a degree of pulsation of convective cooling would make it necessary to represent the heat flux to the study plants as both a mean value and the variation about that mean. Here again, we find that by relaxing just one of the assumptions in our hypothetical study we have introduced variability into the system. Further interesting dynamics would likely be uncovered by relaxing the contributing plant species and spatial distribution and structure of vegetation assumptions.

3.3. Fire Complex Scale

Pushing our hypothetical series of studies to landscape scales elucidates the fire behavior involved in a wildland fire complex. Thus, the study objectives also shift in scale to investigate the dominant flow mechanisms involved in perturbing a fire complex in a specific region. A traditional approach might make the following assumptions: Heat flux is sufficiently high to consume all combustible material; flammability no longer plays a role in local fire behavior; meso-scale atmospheric flow no longer perturbs the fire complex, and there is an excess of oxygen available in the ambient air.

Our expanded hypothetical study has set up a classic example of a "buoyancy-driven" wildfire, the dynamics of which still challenge our understanding of fire behavior at this scale (e.g., References [39,40]). If we remove the assumption that the micro- to meso-scale atmospheric flow no longer perturbs the fire complex, there is no longer a declaration of dominant forcing mechanisms. Now there can be a spectrum of forcing and damping energy sources that span from a buoyancy-dominated system to one where only the local atmospheric dynamics perturb the system. This approach furthers the opportunity for considering multiple scales, from the coexistence of flow perturbation dynamics to the addition of other sources, such as synoptic atmospheric flow [20,21].

When driving flow mechanisms are no longer assumed, this also advances considerations of the obscuring influence that smoke emissions have on surface solar heating and, thus, local atmospheric boundary layer dynamics and fuel moisture. By removing assumptions on dominant flow mechanisms, a more complete picture of the ventilation of the combustion zone, and, thus, the combustion kinetics, can be realized. This removal of assumed dominance also allows for a more thorough treatment of the flow perturbations associated with complex terrain or fuel treatments (e.g., [28,41])—topics ripe for further discovery.

Given that our hypothetical study objectives focus on the interaction of multiple fires that form the complex, the flow interactions between these seemingly separate systems is critical to understanding everything from the merging of "separated" fires (i.e., junction fires; Reference [39]) to the interaction of smoke and embers among these fires [42]. The fluctuations in production of particulates and gaseous species, including water vapor in the smoke plume, are driven by combustion kinetics [43,44]. Likewise, the interaction between changing combustion kinetics, heat transfer, flow dynamics, and flammability all intersect in the development and persistence of ember production [45]. As a closing note on this particular scenario, loosening the assumptions of flammability to allow for variations in spatial arrangement, moisture, and plant species involved to inform formation and movement of the system may stimulate understanding of the "erratic" nature of these large events.

4. Conclusions

The assumption of steady-state dynamics in wildland fire behavior is a legacy that limits the opportunity for advancement of mechanisms involved in understanding fire spread. The very definition of fire behavior in this traditional context stifles innovation, understanding, and application. By systematically releasing traditional simplifications, the study of fire behavior can move beyond steady-state dynamics and address the complex questions fundamental to a greater understanding of wildland fires.

Expanding complexity and integration of historically separate research foci offers tremendous potential to further develop and refine fire behavior theory. A current significant challenge in advancing fire behavior science is the difficulty in collecting quantifiable, in-situ measures of fire behavior. We argue that by broadening the scope of fire behavior research, new technologies (e.g., acoustic emissions as a combustion remote sensing technique [46]) and tools will emerge organically References [35,47–49]. The three brief scenarios were intended to highlight the expanding opportunities currently available in fire behavior research by embracing the inherent variation of wildland fire behavior as its fundamental attribute. Through exploring these scenarios, we illustrated the critical importance that scale and variability—rather than a focus on steady states and central tendencies—can play in more complex systems and across scales. We have argued here that by distilling information down as it is passed between seemingly disparate research foci, the information that can enrich our understanding of fire behavior is lost. Ultimately, this refined approach to fire behavior research will allow for more mechanistic prediction of fire behavior in an increasingly novel and dynamic environment.

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References

1. Rothermel, R.C. *A Mathematical Model for Predicting Fire Spread in Wildland Fuels*; Research Paper INT-115; USDA Forest Service Intermountain Forest and Range Experiment Station: Ogden, UT, USA, 1972.
2. Byram, G.M. Combustion of Forest Fuels. In *Forest Fires: Control and Use*; McGraw-Hill Book Company: New York, NY, USA, 1959; pp. 61–89.
3. Albini, F.A. A model for fire spread in wildland fuels by radiation. *Combust. Sci. Technol.* **1985**, *42*, 229–258. [CrossRef]
4. Van Wagner, C.E. A simple fire-growth model. *For. Chron.* **1969**, *45*, 103–104. [CrossRef]
5. Sullivan, A.L. Wildland surface fire spread modelling, 1990–2007. 1: Physical and quasi-physical models. *Int. J. Wildland Fire* **2009**, *18*, 349–368. [CrossRef]
6. Finney, M.A. *FARSITE: Fire Area Simulator-Model Development and Evaluation*; Res Pap RMRS-RP-4 Revis. 2004; U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: Ogden, UT, USA, 1998. [CrossRef]
7. Heinsch, F.A.; Andrews, P.L. *BehavePlus Fire Modeling System, Version 5.0: Design and Features*; Gen Tech Rep RMRS-GTR-249; U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: Fort Collins, CO, USA, 2010. [CrossRef]
8. Coen, J.L.; Cameron, M.; Michalakes, J.; Patton, E.G.; Riggan, P.J.; Yedinak, K.M. WRF-Fire: Coupled weather-wildland fire modeling with the weather research and forecasting model. *J. Appl. Meteorol. Climatol.* **2013**, *52*, 16–38. [CrossRef]
9. Coen, J.L. Simulation of the Big Elk Fire using coupled atmosphere-fire modeling. *Int. J. Wildland Fire* **2005**, *14*, 49–59. [CrossRef]
10. Taylor, S.W.; Wotton, B.M.; Alexander, M.E.; Dalrymple, G.N. Variation in wind and crown fire behaviour in a northern jack pine-black spruce forest. *Can. J. For. Res.* **2004**, *34*, 1561–1576. [CrossRef]
11. Cruz, M.G.; Alexander, M.E. Uncertainty associated with model predictions of surface and crown fire rates of spread. *Environ. Model. Softw.* **2013**, *47*, 16–28. [CrossRef]
12. Ottmar, R.D.; Hiers, J.K.; Butler, B.W.; Clements, C.B.; Dickinson, M.B.; Hudak, A.T.; O'Brien, J.J.; Potter, B.E.; Rowell, E.M.; Strand, T.M.; et al. Measurements, datasets and preliminary results from the RxCADRE project—2008, 2011 and 2012. *Int. J. Wildland Fire* **2016**, *25*, 1–9. [CrossRef]
13. Jolly, W.M.; Johnson, D.M. Pyro-ecophysiology: Shifting the paradigm of live wildland fuel research. *Fire* **2018**, *1*, 8. [CrossRef]
14. Finney, M.A.; Cohen, J.D.; McAllister, S.S.; Jolly, W.M. On the need for a theory of wildland fire spread. *Int. J. Wildland Fire* **2013**, *22*, 25–36. [CrossRef]
15. Cruz, M.G.; Alexander, M.E.; Sullivan, A.L. Mantras of wildland fire behaviour modelling: Facts or fallacies? *Int. J. Wildland Fire* **2017**, *26*, 973–981. [CrossRef]
16. Tieszen, S.R. On the fluid mechanics of fires. *Annu. Rev. Fluid Mech.* **2001**, *33*, 67–92. [CrossRef]
17. Wallace, J.M.; Hobbs, P.V. Forest Canopy Effect. In *Atmospheric Science*; International Geophysics; Academic Press, Elsevier: Burlington, MA, USA, 2006; Volume 92, pp. 410–411.
18. Campbell, G.S.; Norman, J.M. Finding the zero plane displacement and roughness length. In *An Introduction to Environmental Biophysics*; Springer: New York, NY, USA, 1998; pp. 68–74.
19. Varner, J.M.; Kane, J.M.; Kreye, J.K.; Engber, E. The flammability of forest and woodland litter: A synthesis. *Curr. For. Rep.* **2015**, *1*, 91–99. [CrossRef]
20. Potter, B.E. Atmospheric interactions with wildland fire behaviour—I. Basic surface interactions, vertical profiles and synoptic structures. *Int. J. Wildland Fire* **2012**, *21*, 779–801. [CrossRef]
21. Potter, B.E. Atmospheric interactions with wildland fire behaviour—II. Plume and vortex dynamics. *Int. J. Wildland Fire* **2012**, *21*, 802–817. [CrossRef]
22. Zhou, X.; Weise, D.R.; Mahalingam, S. Experimental measurements and numerical modeling of marginal burning in live chaparral fuel beds. *Proc. Combust. Inst.* **2005**, *30*, 2287–2294. [CrossRef]

23. Smith, A.M.S.; Sparks, A.M.; Kolden, C.A.; Abatzoglou, J.T.; Talhelm, A.F.; Johnson, D.M.; Boschetti, L.; Lutz, J.A.; Apostol, K.G.; Yedinak, K.M.; et al. Towards a new paradigm in fire severity research using dose–response experiments. *Int. J. Wildland Fire* **2016**, *25*, 158–166. [CrossRef]
24. Anderson, H.E. Moisture diffusivity and response time in fine forest fuels. *Can. J. For. Res.* **1990**, *20*, 315–325. [CrossRef]
25. Finney, M.A.; Cohen, J.D.; Forthofer, J.M.; McAllister, S.S.; Gollner, M.J.; Gorham, D.J.; Saito, K.; Akafuah, N.K.; Adam, B.A.; English, J.D. Role of buoyant flame dynamics in wildfire spread. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 9833–9838. [CrossRef] [PubMed]
26. Cunningham, P.; Linn, R.R. Numerical simulations of grass fires using a coupled atmosphere-fire model: Dynamics of fire spread. *J. Geophys. Res. Atmos.* **2007**, *112*. [CrossRef]
27. Yashwanth, B.L.; Shotorban, B.; Mahalingam, S.; Weise, D.R. An investigation of the influence of heating modes on ignition and pyrolysis of woody wildland fuel. *Combust. Sci. Technol.* **2015**, *187*, 780–796. [CrossRef]
28. Sullivan, A.L. Inside the inferno: Fundamental processes of wildland fire behaviour—II. Heat transfer and interactions. *Curr. For. Rep.* **2017**, *3*, 150–171. [CrossRef]
29. Sullivan, A.L. Inside the inferno: Fundamental processes of wildland fire behaviour—I. combustion chemistry and heat release. *Curr. For. Rep.* **2017**, *3*, 132–149. [CrossRef]
30. Kreye, J.K.; Hiers, J.K.; Varner, J.M.; Hornsby, B.S.; Drukker, S.; O'Brien, J.J. Effects of solar exposure and litter position on forest floor moisture dynamics: Overstory structure and species matter. *Can. J. For. Res.* **2018**. in review.
31. Pausas, J.G.; Keeley, J.E.; Schwilk, D.W. Flammability as an ecological and evolutionary driver. *J. Ecol.* **2017**, *105*, 289–297. [CrossRef]
32. Schwilk, D.W. Dimensions of plant flammability. *New Phytol.* **2015**, *206*, 486–488. [CrossRef] [PubMed]
33. Ryan, K.C.; Knapp, E.E.; Varner, J.M. Prescribed fire in North American forests and woodlands: History, current practice, and challenges. *Front. Ecol. Environ.* **2013**, *11*, e15–e24. [CrossRef]
34. Hiers, J.K.; O'Brien, J.J.; Mitchell, R.J.; Grego, J.M.; Loudermilk, E.L. The wildland fuel cell concept: An approach to characterize fine-scale variation in fuels and fire in frequently burned longleaf pine forests. *Int. J. Wildland Fire* **2009**, *18*, 315–325. [CrossRef]
35. Clements, C.B.; Zhong, S.; Goodrick, S.; Li, J.; Potter, B.E.; Bian, X.; Heilman, W.E.; Charney, J.J.; Perna, R.; Jang, M.; et al. Observing the dynamics of wildland grass fires: FireFlux—A field validation experiment. *Bull. Am. Meteorol. Soc.* **2007**, *88*, 1369–1382. [CrossRef]
36. Achtemeier, G. Field validation of a free-agent cellular automata model of fire spread with fire–atmosphere coupling. *Int. J. Wildland Fire* **2012**, *22*, 148–156. [CrossRef]
37. Smoke management guide for prescribed and wildland fire 2001.
38. Frankman, D.; Webb, B.W.; Butler, B.W. Time-resolved radiation and convection heat transfer in combusting discontinuous fuel beds. *Combust. Sci. Technol.* **2010**, *182*, 1391–1412. [CrossRef]
39. Werth, P.A.; Potter, B.E.; Clements, C.B.; Finney, M.A.; Goodrick, S.L.; Alexander, M.E.; Cruz, M.G.; Forthofer, J.A.; McAllister, S.S. *Synthesis of Knowledge of Extreme Fire Behavior: Volume I for Fire Managers*; Gen. Tech. Rep. PNW-GTR-854; U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: Portland, OR, USA, 2011. [CrossRef]
40. Ottmar, R.; Brown, T.J.; French, N.H.F.; Larkin, N.K. *Fire and Smoke Model Evaluation Experiment (FASMEE) Study Plan 2017*; Joint Fire Sciences Program Project 15-S-01-01; 2017. Available online: https://www.fasmee.net/wp-content/uploads/2017/07/FASMEE_StudyPlan_Final_07-11-17.pdf (accessed on 22 June 2018).
41. Pimont, F.; Parsons, R.; Rigolot, E.; de Coligny, F.; Dupuy, J.-L.; Dreyfus, P.; Linn, R.R. Modeling fuels and fire effects in 3D: Model description and applications. *Environ. Model. Softw.* **2016**, *80*, 225–244. [CrossRef]
42. Liu, Y.; Achtemeier, G.L.; Goodrick, S.L.; Jackson, W.A. Important parameters for smoke plume rise simulation with Daysmoke. *Atmospheric Pollut. Res.* **2010**, *1*, 250–259. [CrossRef]
43. Ward, D.E.; Hardy, C.C. Smoke emissions from wildland fires. *Environ. Int.* **1991**, *17*, 117–134. [CrossRef]
44. Achtemeier, G.L. On the formation and persistence of superfog in woodland smoke. *Meteorol. Appl.* **2009**, *16*, 215–225. [CrossRef]
45. Thomas, J.C.; Mueller, E.V.; Santamaria, S.; Gallagher, M.; El Houssami, M.; Filkov, A.; Clark, K.; Skowronski, N.; Hadden, R.M.; Mell, W.; et al. Investigation of firebrand generation from an experimental fire: Development of a reliable data collection methodology. *Fire Saf. J.* **2017**, *91*, 864–871. [CrossRef]

46. Yedinak, K.M.; Anderson, M.J.; Apostol, K.G.; Smith, A.M.S. Vegetation effects on impulsive events in the acoustic signature of fires. *J. Acoust. Soc. Am.* **2017**, *141*, 557–562. [CrossRef] [PubMed]
47. Grumstrup, T.P.; McAllister, S.S.; Finney, M.A. Qualitative flow visualization of flame attachment on slopes. Presented at U. S. National Combustion Meeting Organized by the Eastern States Section of the Combustion Institute, College Park, MD, USA, 23–26 April 2017; p. 6.
48. Dickinson, M.B.; Hudak, A.T.; Zajkowski, T.; Loudermilk, E.L.; Schroeder, W.; Ellison, L.; Kremens, R.L.; Holley, W.; Martinez, O.; Paxton, A.; et al. Measuring radiant emissions from entire prescribed fires with ground, airborne and satellite sensors—RxCADRE 2012. *Int. J. Wildland Fire* **2016**, *25*, 48–61. [CrossRef]
49. O'Brien, J.J.; Loudermilk, E.L.; Hornsby, B.; Hudak, A.T.; Bright, B.C.; Dickinson, M.B.; Hiers, J.K.; Teske, C.; Ottmar, R.D. High-resolution infrared thermography for capturing wildland fire behaviour: RxCADRE 2012. *Int. J. Wildland Fire* **2016**, *25*, 62–75. [CrossRef]