Weather, Fuels, Fire Behavior, Plumes, and Smoke—The Nexus of Fire Meteorology

Scott L. Goodrick, Timothy J. Brown, and W. Matt Jolly

In a pair of review papers, Potter (2012a, 2012b) summarized the significant fire weather research findings over about the past hundred years. Our scientific understanding of wildland fire-atmosphere interactions has evolved: from simple correlations supporting the notion that hot, dry, and windy conditions lead to more intense fires, we have moved towards more mechanistic and physical descriptions of governing processes such as fuel moisture dynamics, wind-driven fire spread, the influence of vortices, and plume dynamics. Our advances are important not only for the sake of scientific knowledge but also for the sake of transferring new knowledge into applications for decisionmaking.

However, there is still much we do not understand. Potter (2012a, 2012b) offers ideas for future research that could prove particularly beneficial. How do vertical wind profiles and wind shear influence fire behavior? What atmospheric processes transport dry, high-momentum air from the upper and middle portions of the troposphere down near the Earth's surface, and how do these processes interact with the atmospheric boundary layer and, eventually, a wildland fire? At what scales does wind shear contribute most strongly to vortex formation? How does the heat and moisture released through combustion interact with ambient atmospheric stability? How do variations in sunshine influence fuel moistures, stability, and airflow in and around a fire?

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Though by no means exhaustive, such research questions indicate that fire-atmosphere interaction research will require considerably more and different data than in the past. Fire-atmosphere interaction studies have relied on fairly simple fire metrics, such as area burned; change in fire perimeter or mean spread rate; and predominately surface weather observations of temperature, atmospheric moisture content, and wind speed as well as wind direction. Answering the questions raised by Potter (2012a, 2012b) will require more. We will need more detailed fire information, tracking not only the fire spread rate but also heat and moisture fluxes to the atmosphere, varying in both space and time. We will need more detailed weather information, moving beyond just surface conditions at a few locations to include local estimates of three-dimensional atmospheric structure and the evolution of those estimates.

This article focuses on what we can do to move forward with these and other research questions that require "more." First, the authors examine some of the technologies available for collecting the needed data and some of the field projects already working to collect such data. Next, the article outlines some of the advances in computing that are giving researchers new ways to examine fire-atmosphere interactions. However, this article is by no means a definitive look at technologies that will be important to fire-atmosphere research; the most important technologies may not have been thought of yet.

New Ways of Looking at Fires

Wildland fires are difficult to measure and study. High temperatures and high variability in both space and time make measuring fire attributes both difficult and dangerous. Remote sensing of wildland fires is an area of research that has emerged over the last two decades, with a variety of instruments capable of observing fires across a broad range of space and time scales.

Satellites provide some of the coarsest information in both space and time. The Hazard Mapping System of the National Oceanic and Atmospheric Administration (Rolph and others 2009) integrates information from a number of satellites

Scott Goodrick is a research meteorologist for the Forest Service, Southern Research Station, Athens, GA; Timothy J. Brown is a research professor with the Division of Atmospheric Sciences at the Desert Research Institute, Reno, NV; and Matt Jolly is a research ecologist for the Forest Service, Rocky Mountain Research Station, Missoula, MT.

to create daily maps of fire hotspots and smoke plumes. The finest spatial scale represented on these maps is 500 meters for detections by the National Aeronautics and Space Administration's MODIS instrument. Efforts have been made to estimate fire sizes from this coarse spatial data by relating satellite-measured brightness temperature to burned area, information that can be used to approximate fire progressions.

For the purpose of studying wildland fires, satellite remote sensing is of limited value because the data you get is high in either spatial resolution or temporal resolution but not both. Polar orbiting satellites travel in a low Earth orbit, achieving spatial resolutions as fine as 1 meter, but the satellites pass over a given location no more than every 1 to 3 days. Satellites in geosynchronous orbit continually view the same portion of the Earth's surface, updating each pixel of their image every few minutes. Spatial resolution of geosynchronous images is roughly 1 to 4 kilometers, for a coverage by each pixel of an area from about 250 to 4,000 acres (100–1,620 ha). The primary benefit from such products is a "big-picture" view of burning across an entire region, making this type of data a good fit for synoptic and climate studies.

Radar is another means of examining fires, specifically their plume structure. Hanley and others (2013) used data from National Weather Service NEXRAD radar to examine interactions between an approaching sea breeze front and a prescribed fire on the Apalachicola National Forest in Florida (fig. 1). The study related the passage of the front over the fire to observed plume structures and on-the-ground fire behavior to show how a sea breeze front can trigger erratic fire behavior. Doppler radars such as the NEXRAD allow us to examine the structure of the plume, as indicated by the base reflectivity, as well as winds at different heights within the plume. However, as distance from the radar increases, the lowest part of the plume observable by the radar increases in height, limiting the usefulness of radar in studying fire plumes. Portable radars help get around this limitation because not all fires are as conveniently located near a National Weather Service radar.

Similar in many ways to radar, Doppler lidar is another tool now being applied to examine fire-atmosphere interactions. For example, Charland and Clements (2013) used a ground-based scanning Doppler lidar to study airflow around the plume of a prescribed fire. The lidar revealed the development of a convergence downwind of the plume along with elevated radial velocities at the plume boundary that indicated fire-induced enhancement of the inflow into the base of the convection column. Hiscox and others (2006) used lidar data to estimate appropriate dispersion coefficients for smoke modeling, work previ-

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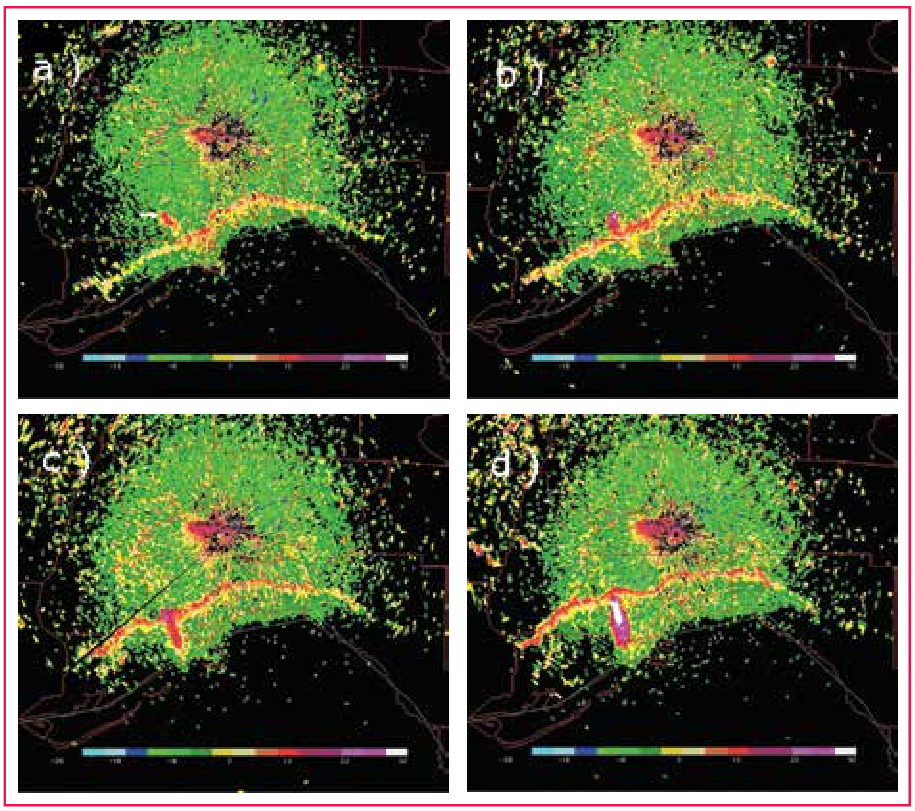

Figure 1—*Interaction of wildland fire with a sea breeze front on the Apalachicola National Forest in Florida on April 5, 2004, as shown by radar reflectivity (dBZ). The fire is located at the white arrow in (a), and the sea breeze front is the arc of elevated reflectivity in the lower half of each image. As the sea breeze front passes over, the fire changes in size and shape from 1828 UTC (a), to 1927 UTC (b), to 2025 UTC (c), and finally to 2124 UTC (d).*

ously conducted primarily through wind tunnel experiments.

Advances are also being made in characterizing the environmental conditions on a wildland fire. Fire researchers are placing sensor packages directly in the path of an approaching fire to measure the heat produced by the fire and the horizontal and vertical wind flows as fires approach and pass (Butler and others 2010). These packages can give researchers valuable information for use in evaluating wildland fire behavior models. They offer information about the rate of energy release from wildland fires and might improve our ability to better predict how fires interact with the atmosphere.

Infrared imagery, both airborne and in situ, has evolved tremendously over the years. It is another means of collecting detailed information about fire behavior. For over 40 years, wildland firefighters have used infrared sensors to detect, monitor, and direct fire suppression and mop up operations (Zajkowski and others 2003). Output from early airborne infrared sensors took the form of print imagery, useful for operations but of limited value for researchers. Some early infrared sensors were limited by saturation because they were not designed for the high infrared radiances typical of a wildland fire. More recent sensors have been specifically designed for wildland fire applications. The FireMapper thermal-imaging radiometer allows quantitative measurements of fire spread rates, fire temperatures, radiant energy flux, residence time, and fire line geometry (fig. 2) (Riggan and others 2010).

Like airborne infrared imagery, ground-based infrared imagery has advanced as a source of fire-related data for research. Coen and others (2004) studied the dynamics of crown fire by deriving a wind field from an infrared imaging camera using image flow analysis techniques. Their study helped to illustrate the link between convective updrafts and changes in surface airflow. Loudermilk and others (2012) combined lidar measurements of fuel structure and infrared imagery taken from a height of 7 meters to link fuelbed continuity and the heterogeneity associated with fuel types to fire behavior at the submeter scale. Infrared imagery has evolved into a tool that offers fire data across a range of space and time scales.

Figure 2—*FireMapper thermal image of the Esperanza Fire, showing ground surface temperatures as viewed from above on October 26, 2006, between 14:07 and 14:17 PDT.*

Prescribed Fires as Laboratories

The scientific study of wildfire dynamics is difficult because wildfires are not repeatable and the conditions that fires burn under cannot be controlled. It is difficult to know the prefire conditions since we do not have prior knowledge of when and where a wildfire will occur. Prescribed fires give researchers a level of control and repeatability not possible with wildfires.

Although prescribed fire has been used for studies such as the International Crown Fire Modeling Experiment (Alexander and others 1998), Wildfire Experiment (Radke and others 2000), and the FROSTFIRE experiment (Wilmore and others 1998; Coen and others 2004), studies are now being designed with a focus on fire–atmosphere interactions. In the FireFlux experiment, Clements and others (2007) examined the structure of a flaming front in a tallgrass prairie by capturing measurements of winds and heat fluxes during the fire's passage. These measurements were accompanied by nearby vertical profiles and surface weather stations recording time series of temperature, humidity, and wind.

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The Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE) expanded upon the ideas of FireFlux by conducting three sets of intensively measured experimental burns (in 2008, 2011, and 2012). The experiment was in simple fuelbeds—grass and shrubs—at Eglin Air Force Base in Florida. Over 90 scientists and technicians participated in collecting data on fuels, fire behavior, fire effects, meteorology, and smoke dispersion. The experiment was designed, in part, to collect datasets suitable for evaluating coupled fire–atmosphere models, smoke production and dispersion models, and fire effects models. Achtemeier and others (2012) published one of the first attempts at modeling one of the RxCADRE burns, a 1,650-acre (668-ha) aerial ignition. The simulation illustrated the complex interactions between fire and atmosphere and how they affect smoke plume structure (fig. 3).

Computer Models as Laboratories

Prescribed fires offer researchers a very modest level of control and reproducibility for their experiments, but this is nothing compared to the degree of control provided by the coupled fire–atmosphere models in use today. A coupled model is simply the joining of two models such that each model influences the other's results. In this case, a model of the atmosphere is joined to a model of a wildland fire such that the fire alters atmospheric temperatures, moisture, and winds, which in turn influence the evolution of the fire.

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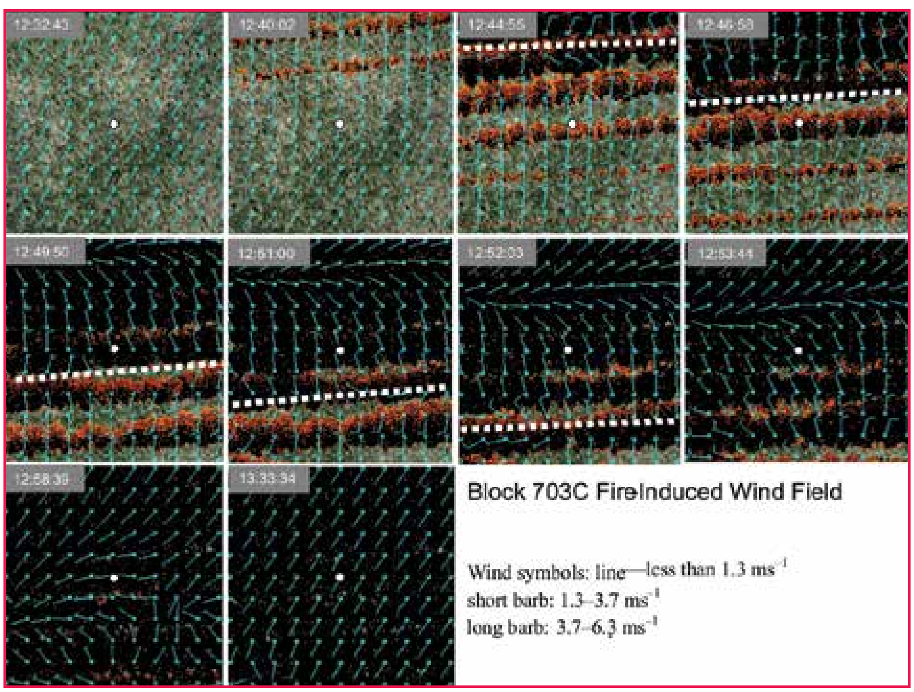

Figure 3—*Simulated time evolution of wind field during a simulated aerial ignition burn. The ignition pattern influences the wind field and the development of convergence zones (white dotted line), indicating an area of strong updrafts.*

Clark and others (1996) described one of the earliest examples of a coupled fire–atmosphere model, developed at the National Center for Atmospheric Research. The model merged a detailed atmospheric model with a fairly simple fire description based on the Rothermel (1972) spread model. Early results helped researchers understand some of the complex interactions that play a role in the development of fingers along a fire front. The model of Clark and others (1996) has evolved over the years into WRF–SFire (Mandel and others 2011) and CAWFE (Coen 2013).

Over the years, other coupled fire–atmosphere models have given more complete descriptions of the combustion portion of the problem. They include FIRETEC, developed at the Los Alamos National Laboratory (Linn and others 2002); and the Wildland Urban Interface Fire Dynamics Simulator, derived from the Fire Dynamics Simulator developed at the National Institute of Standards (Mell and others 2007; McGrattan and others 2010). Such models have been used to study a range of questions: how topography influences fire behavior (Linn and others 2007; Pimont and others 2012); how multiple fire lines interact (Morvan and others 2013); and how effective fuel treatments are (Cassagne and others 2011). Even without coupling, high-resolution atmospheric models have been useful in studying aspects of extreme fire behavior such as vortex dynamics (fig. 4) (Cunningham and others 2005).

Figure 4—*Idealized simulation of an airflow over a heat source, producing a pair of counterrotating vortices at the head of the fire (top). Aerial view from a real burn showing similar plume structures (bottom). Photo: Bret Butler, Forest Service.*

Interactions Between Terrain and Weather

Wildland fire behavior is dominated by fuel availability, terrain shape and orientation (topography), and local weather conditions. However, these factors are not independent, and topographic variations can heavily influence local weather conditions. Historically, wildland fires were simulated by assuming that wind speed and wind direction were constant across the entire burning area for a given time. Advances in wind modeling are significantly improving our ability to reduce coarse numerical weather model predictions, to predict fine-scale variations in wind speed and wind direction, and to depict solar-radiation-induced diurnal wind flow patterns (Forthofer and others 2014).

Furthermore, terrain can influence microclimates, which in turn can affect fine-scale fuel moisture and subsequent fuel availability (Holden and Jolly 2011). Ultimately, interactions between terrain and weather must be fully understood in order to use coarse-scale weather conditions to predict wildland fire combustion processes and subsequent fire–atmosphere coupling. Future work will improve and refine our ability to characterize microclimatic conditions and their influence on fire behavior.

Bringing It All Together

New technologies for looking at wildland fires and the structure of their plumes, coupled with advances in our ability to simulate wildland fires and their complex feedbacks to the atmosphere, are a solid foundation for answering a variety of fire-related questions. Lidar measurements of the flow field around fires can help researchers understand how vertical wind profiles and wind shear influence fire behavior. Advances in computer modeling will give insight into various questions regarding scale interactions and processes like vortex formation. Many of the questions posed by Potter (2012a, 2012b) as areas for fruitful future research are far more amenable to study now than they would have been in the past.

A 2015 project supported by the Joint Fire Science Program, still in the planning phase, is designed to yield novel critical observational data necessary to build and validate next-generation modeling systems for fire growth and danger, fuels consumption and emissions, smoke plumes, and smoke impacts. If fully funded, the project will be a multiagency, multiyear field campaign conducted across a variety of fuelbeds, including complex fuels, and over a variety of burn conditions, including large burns designed to simulate wildfires. This type of data collection is important because improvements are needed in both the underlying understanding and the overall accuracy of models central to operational decisionmaking in managing wildland fire and the resulting smoke.

References

Achtemeier, G.L; Goodrick, S.L.; Liu, Y. 2012. Modeling multiple-core updraft plume rise for an aerial ignition prescribed burn by coupling daysmoke with a cellular automata fire model. Atmosphere. 3: 352–376.

Alexander, M.E.; Stocks, B.J.; Wotton, B.M.; [and others]. 1998. The International Crown Fire Modeling Experiment: An overview and progress report. Preprints, Second Symposium on Fire and Forest Meteorology; 11–16 January 1998; Phoenix, AZ. American Meteorological Society: 20–23.

Butler, B.W.; Jimenez, D.; Forthofer, J.; [and others]. 2010. A portable system for characterizing wildland fire behavior. Proceedings of the 6th International Conference on Forest Fire Research (CD–ROM); 15–18 November 2010; University of Coimbra, Coimbra, Portugal.

Cassagne, N.; Pimont, F.; Dupuy, J.-L.; [and others]. 2011. Using a fire propagation model to assess the efficiency of prescribed burning in reducing the fire hazard. Ecological Modelling. 222(8): 1502–1514. doi:10.1016/j.ecolmodel.2011.02.004.

Charland, A.M.; Clements, C.B. 2013. Kinematic structure of a wildland fire plume observed by Doppler lidar. Journal of Geophysical Research: Atmospheres. 118(8): 3200–3212. doi:10.1002/jgrd.50308.

Clark, T.L.; Jenkins, M.A.; Coen, J.; Packham, D. 1996. A coupled atmosphere–fire model: convective feedback on fire-line dynamics. Journal of Applied Meteorology. 35: 875–901.

Clements, C.; Zhong, S.; Goodrick, S.; [and others]. 2007. Observing the dynamics of wildland grass fires. Bulletin of the American Meteorological Society. 88(9): 1369–1382. doi:10.1126/science.1244843

Coen, J.L. 2013. Modeling wildland fires: A description of the Coupled Atmosphere–Wildland Fire Environment model (CAWFE). NCAR Technical Note NCAR/TN–500þSTR. <http://nldr.library.ucar.edu/repository/collections/TECH–NOTE–000–000–000–866> (last accessed September 2016).

Coen, J.; Mahalingam, S.; Daily, J. 2004. Infrared imagery of crown-fire dynamics during FROSTFIRE. Journal of Applied Meteorology. 43(9): 1241–1259.

Cunningham, P.; Goodrick, S.L.; Hussaini, M.Y.; Linn, R.R. 2005. Coherent vortical structures in numerical simulations of buoyant plumes from wildland fires. International Journal of Wildland Fire. 14: 61–75.

Future work will improve and refine our ability to characterize microclimatic conditions and their influence on fire behavior.

Forthofer, J.M.; Butler, B.W.; Wagenbrenner, N.S. 2014. A comparison of three approaches for simulating fine-scale surface winds in support of wildland fire management. Part I: Model formulation and comparison against measurements. International Journal of Wildland Fire. 23: 969–981.

Hanley, D.E.; Cunningham, P; Goodrick, S.L. 2013. Interaction between a wildfire and the sea-breeze front. In: Qu, J.J.; Sommers, W.T.; Yang, R.; Riebau, A.R. (eds.). Remote sensing and modeling applications to wildland fires. Beijing, China: Tsinghua University Press and New York: Springer: 81–98.

Hiscox, A.; Napro, C.; Miller, D. 2006. On the use of lidar images of smoke plumes to measure dispersion parameters. Journal of Atmospheric and Oceanic Technology. 23: 1150–1154.

Holden, Z.A.; Jolly, W.M. 2011. Modeling topographic influences on fuel moisture and fire danger in complex terrain to improve wildland fire management decision support. Forest Ecology and Management. 262: 2133–2141.

Linn, R.R.; Reisner, J.; Colman, J.J.; Winterkamp, J. 2002. Studying wildfire behaviour using FIRETEC. International Journal of Wildland Fire. 11: 233–246.

Linn, R.R.; Winterkamp, J. L.; Edminster, C.; [and others]. 2007. Coupled influences of topography and wind on wildland fire behavior. International Journal of Wildland Fire. 16: 183–195. doi:10.1080/13647830902977570.

Loudermilk, E.L.; O'Brien, J.J.; Mitchell, R.J.; [and others]. 2012. Linking complex forest fuel structure and fire behaviour at fine scales. International Journal of Wildland Fire. 21: 882–893.

Mandel, J.; Beezley, J.D.; Kochanski, A.K. 2011. Coupled atmosphere–wildland fire modeling with WRF 3.3 and SFIRE 2011. Geoscientific Model Development. 4: 591–610.

McGrattan, K.B.; Baum, H.; Rehm, R.; [and others]. 2010. Fire dynamics simulator (version 5) technical reference guide, mathematical model. Vol. 1. NIST, Spec. Pub. 1018–5.

Mell, W.; Jenkins, M.A.; Gould, J.; Cheney, P. 2007. A physics-based approach to modeling grassland fires. International Journal of Wildland Fire. 16(1): 1–22.

Morvan, D.; Meradji, S.; Mell, W. 2013. Interaction between head fire and backfire in grasslands. Fire Safety Journal. 58: 195–203.

Pimont, F.; Dupuy, J.L.; Linn, R.R. 2012. Coupled slope and wind effects on fire spread with influences of fire size: A numerical study using FIRETEC. International Journal of Wildland Fire. 21: 828–842.

Potter, B.E. 2012a. Atmospheric interactions with wildland fire behaviour—I. Basic surface interactions, vertical profiles and synoptic structures. International Journal of Wildland Fire. 21(7): 779–801.

Potter, B.E. 2012b. Atmospheric interactions with wildland fire behaviour—II. Plume and vortex dynamics. International Journal of Wildland Fire. 21(7): 802–817.

Radke, L.F.; Clark, T.L.; Coen, J.L.; [and others]. 2000. The wildfire experiment (WIFE): observations with airborne remote sensors. Canadian Journal of Remote Sensing. 26(5): 406–417.

Riggan, P.J.; Wolden, L.G.; Tissel, R.G.; [and others]. 2010. Remote sensing fire and fuels in southern California. Proceedings of the 3rd Fire Behavior and Fuels Conference; 25–29 October 2010; Spokane, WA. <http://www.fs.fed.us/psw/publications/riggan/psw_2010_riggan002.pdf> (last accessed September 2016).

Rolph, G.D.; Draxler, R.R.; Stein, A.F.; [and others]. 2009. Description and verification of the NOAA Smoke Forecasting System: The 2007 fire season. Weather and Forecasting. 24: 361–378.

Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. Res. Pap. INT–115. Ogden, UT: USDA Forest Service, Intermountain Forest and Range Experiment Station.

Wilmore, R.; Slaughter, K.; Theisen, M.; Roessler, J. 1998. FROSTFIRE research prescribed burn plan. Tech. Rep. Bureau of Land Management, Alaska Fire Service.

Zajkowski, T.; Queen, L.; VanBuren, D. 2003. Infrared field users guide and vendor listings. Salt Lake City, UT: USDA Forest Service Engineering, Remote Sensing Applications Center, RSAC–1309–RPT1. <http://nirops.fs.fed.us/docs/about-more/08-1309-RPT1.pdf> (last accessed September 2016).