Project Title: Fuel Consumption and Smoke Emissions from Landscape-Scale Burns in Eastern Hardwoods

Final Report: JFSP Project Number 06-2-1-33

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For further information go to www.firescience.gov

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ABSTRACT

Our project used remotely-sensed infrared radiation measurements to estimate fuel consumption in eastern mixed-oak forests and facilitated the development of smoke management expertise and processes for complying with EPA regulations in Ohio and Kentucky. As a result of two workshops, Ohio developed a Smoke Management Plan designed to ensure that best management practices were being used across land ownerships and to facilitate mandated information sharing with the Ohio EPA and US EPA. Ohio also established a Prescribed Fire Council as a result of this process. Kentucky opted for a less formal response to EPA regulations, establishing a Prescribed Fire Council to facilitate information sharing and coordination. The workshops offered training in the CONSUME fuel consumption model and the Fuel Characteristics Classification System (FCCS) program allowing land management personnel to estimate consumption for past and upcoming burns as inputs to smoke transport models and as part of their emissions inventory process. Training was provided by the USFS Fire and Environmental Research Applications (FERA) group.

On the research side, five prescribed fires were monitored with aerial and ground-based equipment. The Wildfire Airborne Sensor Platform (WASP) was used on one fire and the WASP-lite system (smaller and less expensive to deploy) was used on the other fires. In addition, a series of outdoor, small plot burn experiments were conducted to provide the link between fire radiant heat release and fuel consumption. A paper describing the theory behind the methods used for analyzing airborne data and identifying gaps in knowledge has been published (Kremens et al. 2010). A second paper describing ground-based measurements of fire heat release and fuel consumption is in review at the International Journal of Wildland Fire and another paper describing the methods for using airborne infrared data to map fuel consumption at the burn unit scale is in review. A thesis describing landscape patterns in fire heat release based on our data has been completed (Suciu 2009) and is the basis for a final paper in progress. Significant technical challenges were encountered in this novel application of airborne remote

sensing to the fuel consumption problem, but those challenges are being met and the technology being developed for future application.

In summary, the project to date has resulted in two smoke management workshops; one paper published in the peer reviewed literature, two papers in review, and one paper in process; and multiple invited and offered presentations and posters. The deliverables can be found on the project website at www.firescience.gov.

BACKGROUND AND PURPOSE

Smoke management is an emerging issue in eastern hardwood forest management, a theme reiterated by both Federal and State land managers. As the acreage burned for ecological restoration and fuel reduction increases, public and agency concerns rise regarding smoke's negative effects on such things as human health, transportation, visibility, and sensitive wildlife species. Regional Haze Rules (Federal Register / Vol. 64, No. 126 / Thursday, July 1, 1999) require that States make "reasonable progress" in reducing effects of pollution (including that from wildland fire) on visibility in Class I areas and to prevent future impairment of visibility. States (and Tribes who choose to participate) are also required to develop Smoke Management Programs (SMP's) to minimize emissions; evaluate (model) smoke dispersion; explore alternatives to fire; and conduct public notification, air quality monitoring, enforcement, surveillance, and program evaluation. At the time this project was funded, a minority of States had completed their SMP's. The need for a boost in smoke modeling capability and development of SMPs in Ohio and Kentucky were paramount justifications for this project. We supported that process through training in the use of key smoke management tools and by facilitating multi-party discussions and working groups.

Ohio and Kentucky, the states in which this project was carried out, encompass a substantial amount of forest dominated by oaks for which historical burning has played a central role (e.g., Dickinson 2006). Decades of effective fire prevention and suppression have all but eliminated fire from these landscapes. The resulting region-wide forest change has often been undesirable. Consequently, we are in a period of increasing prescribed burning activities on State and Federal lands. As well, extensive disturbance by a February, 2003, ice storm in the Wayne National Forest (WNF) and Shawnee State Forest (SSF) in Ohio and bark beetles in the Daniel Boone National Forest (DBNF) in Kentucky have generated heavy woody fuel loads. Fire managers need information for meeting the requirements of current and future regulation.

At the same time that there is an increasing need for smoke management forecasting in eastern hardwood forests, smoke production models have not been validated for hardwood fuels and fires. For instance, CONSUME, a fuel consumption model widely used in smoke management modeling, is only now (with JFSP funding and support and participation from the principals in this project) developing equations specific to eastern US mixed-oak forests. This project developed airborne IR imaging as a method of characterizing fuel consumption over complex eastern hardwood landscapes in order to answer the questions of what quantities are being consumed on average and how that consumption is distributed over landscapes. Those methods are now being applied to additional fires in mixed-oak forests and also in prescribed fires in longleaf pine savannas in the southeastern US. Once the methods are established in prescribed fires, they can also be applied to wildfires.

STUDY DESCRIPTION AND LOCATION

The field work and workshops focused on mixed-oak forest zones of southern Ohio and eastern Kentucky. This area is largely forested and contains the Wayne National Forest, the mixed-oak districts of the Daniel Boone National Forest, various state landholdings, The Nature Conservancy land, and substantial private forest land. Two workshops were held along the Ohio River, forming the border between Ohio and Kentucky. Fire monitoring occurred at Tar Hollow State Forest and the Racoon Ecological Management Area in southeastern Ohio and on several prescribed fire units in the Daniel Boone National Forest (Bear Waller, Powder Mill, and Wolf Pen). More information on study design and locations can be obtained from the publications.

KEY FINDINGS

Fuel consumption vs radiant heat release in spreading fires

Previous work had determined the radiant fraction (i.e., the proportion of theoretical total heat production by a fire dissipated by radiation) from combustion of relatively small quantities of fuel in stationary fires (Figure 1). We determined radiant fraction from fires spreading across 8x8 m (26x26 ft) plots of mixed-oak litter and wood. Knowing the radiant fraction allows one to use infrared imaging to estimate and map fuel consumption at plot and landscape scales. Radiant fractions from our experiments were higher than those from studies that used stationary fires, bolstering the conclusion that we need to learn more about fire heat dissipation under realistic scenarios.

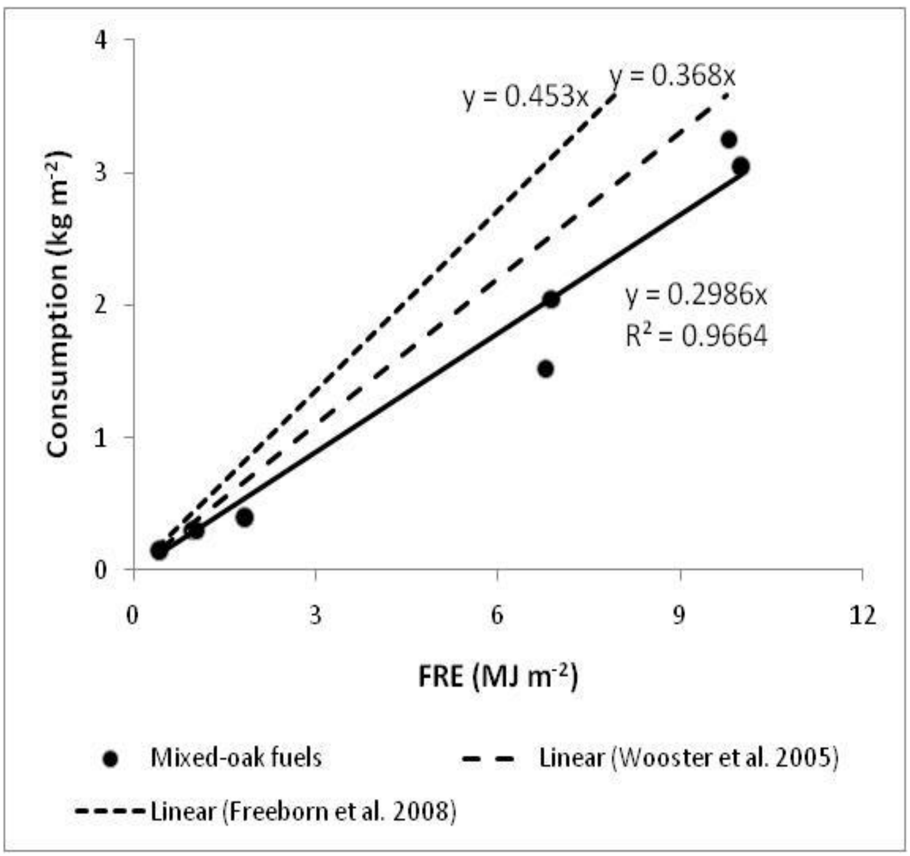

Figure 1. Total fuel consumption as a function fire radiative energy (FRE, kJ m^{-2}) from spreading fires in mixed-oak fuels. Data from stationary fires are given for comparison.

Closing the fire heat budget

The ability to map radiant heat release and consumption is useful, but it would be even more useful to be able to use radiant heat release maps to estimate convective and other forms of heat dissipation. Fire heat budgets have never been fully quantified in the field, that is, coordinated measurements of heat generation by combustion and heat dissipation by radiation, convection, latent heat flux, and soil heating have never been made. Convective heat release accounts for the majority of heat released by fires and is the primary driver of plume development. Latent heat flux at times may also be important in plume development when water vapor produced by combustion condenses in smoke plumes, forming pyrocumulus storm development. Our work made estimates of heat dissipation and underscores the need for coordinated measurements (Figure 2).

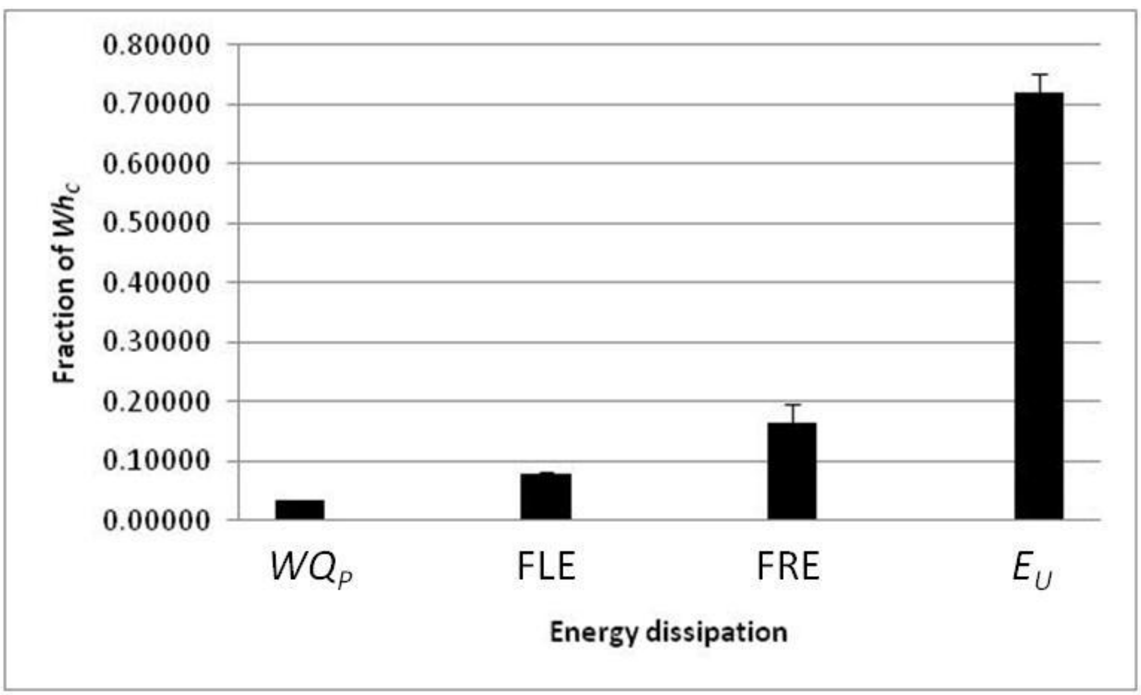

Figure 8

Figure 2. Fraction of total combustion energy (Wh_c) dissipated by fuel pre-heating (WQ_p), fire latent energy (FLE), radiation (FRE), and convection and soil heating (E_U) in mixed-oak surface fires.

Fireline intensity is proportional to peak radiative heat release

Byram's (frontal) fireline intensity (kW m^{-1}) is a standard fire behavior descriptor in research and operations. We found that fireline intensity in spreading fires in our plot experiments was proportional to peak radiant heat release (Figure 3). This is not altogether surprising in that fireline intensity is a function of the rate of fuel consumption. What is surprising is that radiant fraction has no simple relationship to fireline intensity (Figure 4). This is surprising because fireline intensity is closely related to flame length and larger flames should have higher radiant emissivities because they are thicker. Again, more work is needed on heat dissipation from spreading fires.

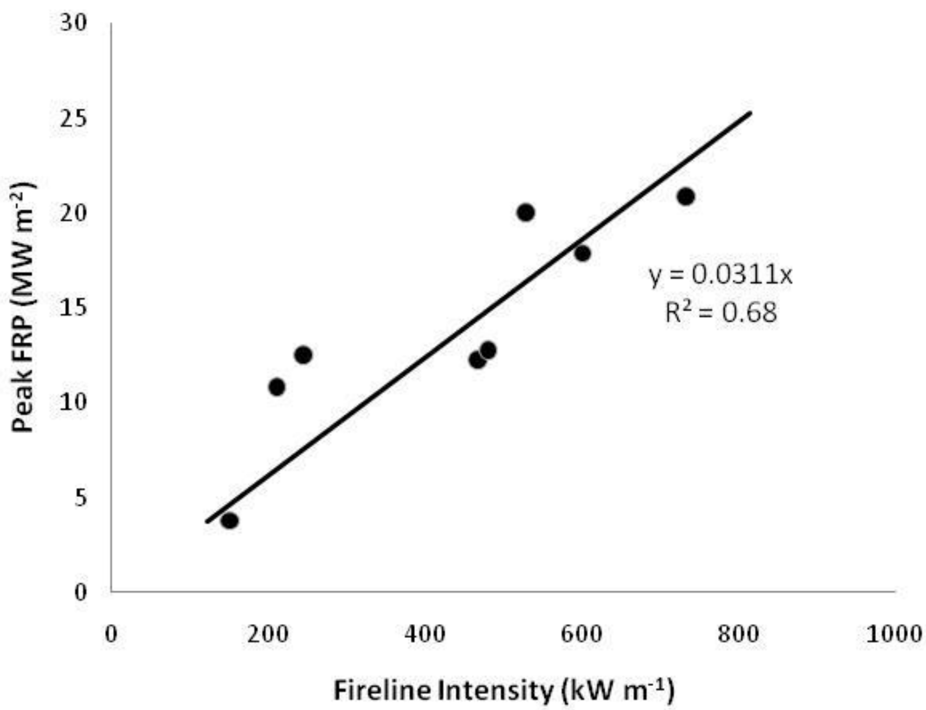

Figure 2. Peak radiative heat release (peak fire radiative power, FRP) is proportional to Byram's fireline intensity calculated from fuel consumption and rate of spread.

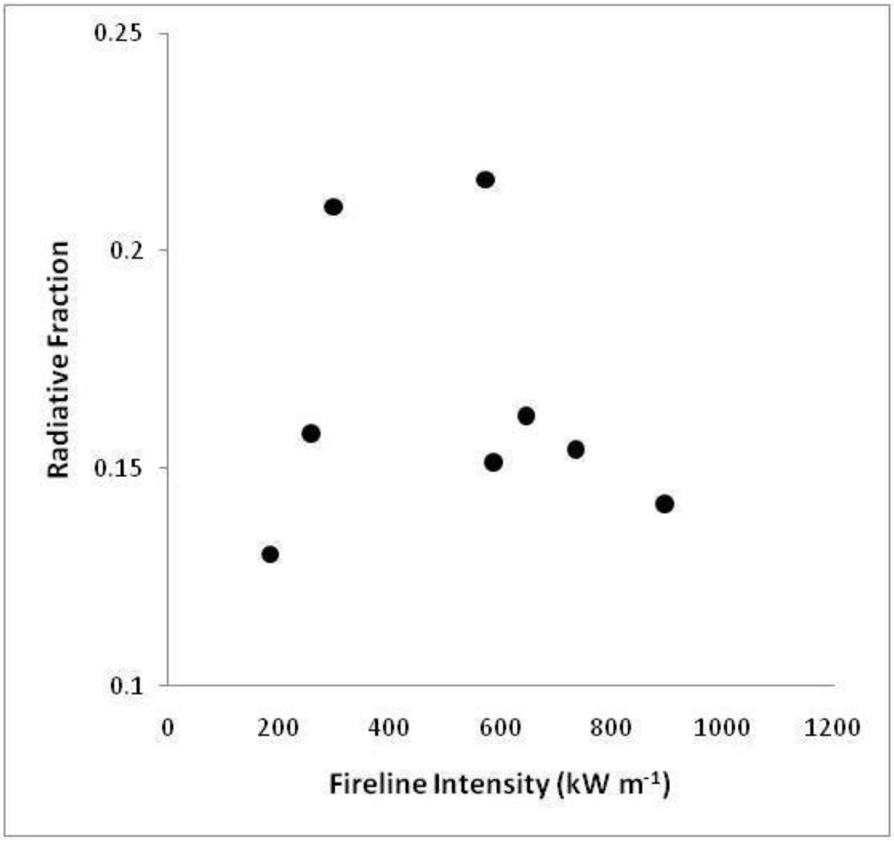

Figure 3. Radiant fraction (the fraction of the theoretical total heat release that is dissipated by radiation) as a function of Byram's fireline intensity. We expected a positive, linear relationship, but the relationship is ambiguous.

Using remote sensing to describe fine-scale fire heat release at a landscape extent

We imaged 5 prescribed fires in mixed-oak forest using the Wildfire Airborne Sensor Platform (WASP) and WASP-lite. To date, we are completing work on imagery from WASP (the Arch Rock fire). We have dual-band data (long-wave and medium-wave infrared), but are currently using the calibrated longwave data because of uncertainty in image co-registration. Use of a single wavelength band is possible because fire temperatures are near constant at 1100 °C (see our in-review International Journal of Wildland Fire paper for a justification of the methods). Figure 4 shows sequential maps of infrared heat release from the Arch Rock prescribed fire. Pixel size is approximately 1 m and spatial extent is ~1 km.

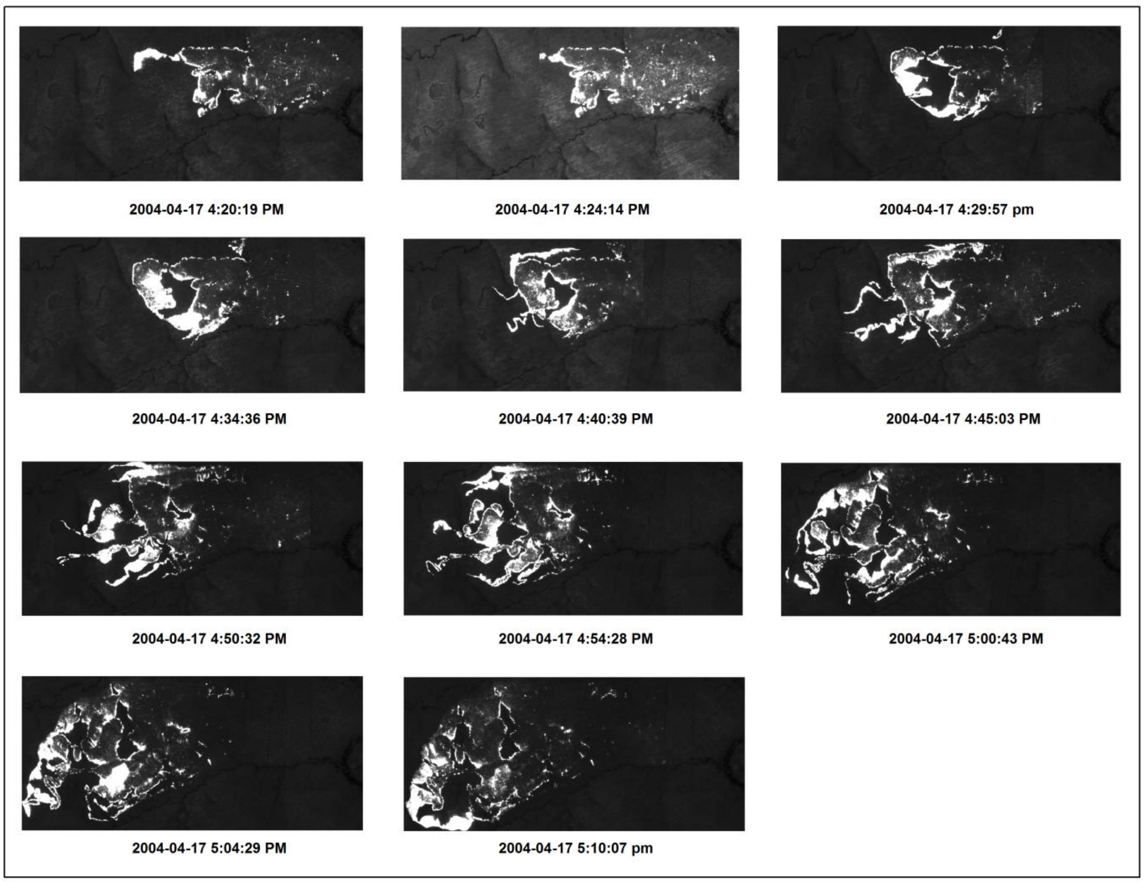

Figure 4. Sequential WASP infrared heat release (FRP) from the Arch Rock prescribed fire. The fire was ignited by hand (drip torch) and ignition proceeded roughly from west to east. Images are approximately 4-6 m apart.

The landscape pattern in fuel consumption estimated from WASP is shown in Figure 5. Fuel consumption is estimated from fire radiated energy (FRE), which is based on the sequential images of fire radiated power (FRP), and the calibration in Figure 1. Mean consumption estimated from WASP radiant heat release closely matches consumption measured on the ground with the exception of fuel jackpots which were not included in the ground sample (Figure 6). Unfortunately, pixel-to-pixel correspondence in fuel consumption is not adequate (Figure 7), indicating a calibration issue associated with using only long-wave information, spatial error in plot positioning and image geo-positioning, or some other problem. We are currently exploring this issue and believe we have a solution. Only categorical information (low, medium, high) heat release information can be used from the WASP-lite datasets because of image saturation. The WASP-lite imagery is adequate for describing ground temperatures prior to burning (which correspond to fuel moisture) and for exploring landscape patterns in heat release.

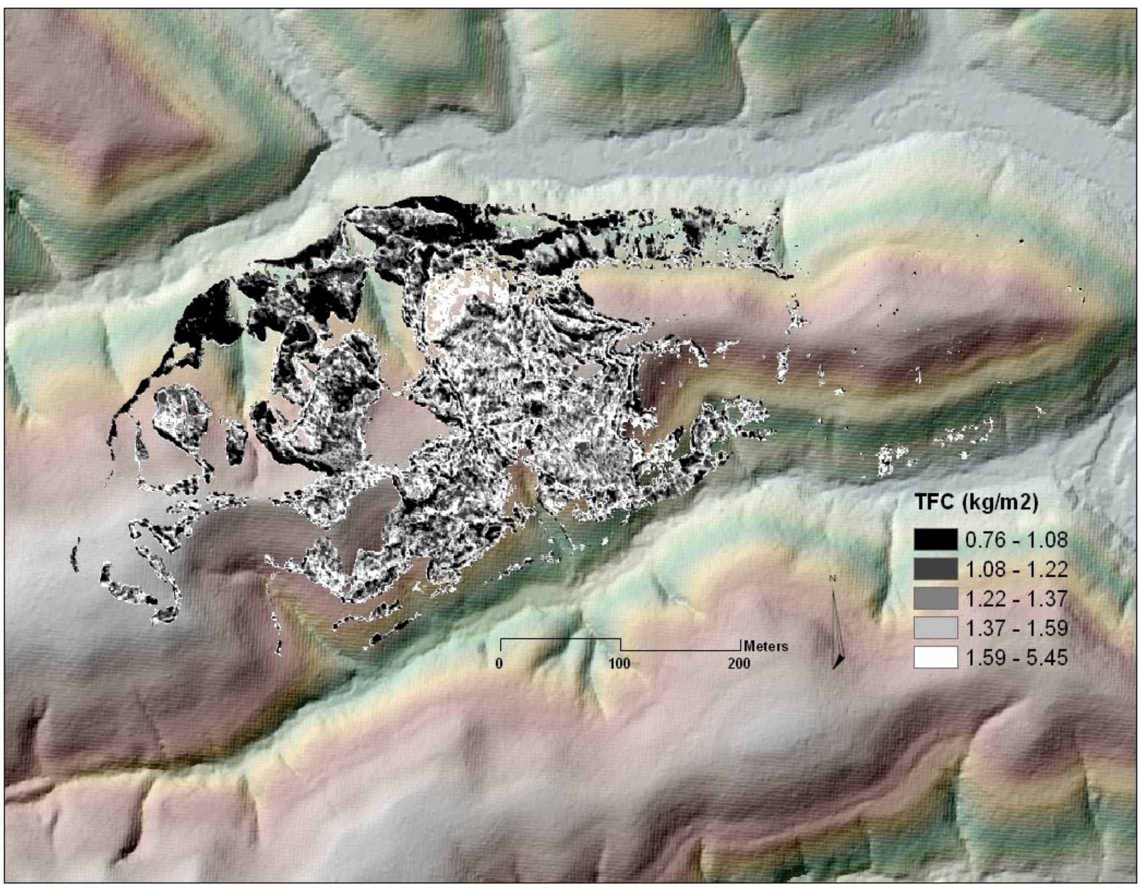

Figure 5. Fuel consumption estimated from fire radiated energy. Note that north-facing, lower slopes exhibited low consumption.

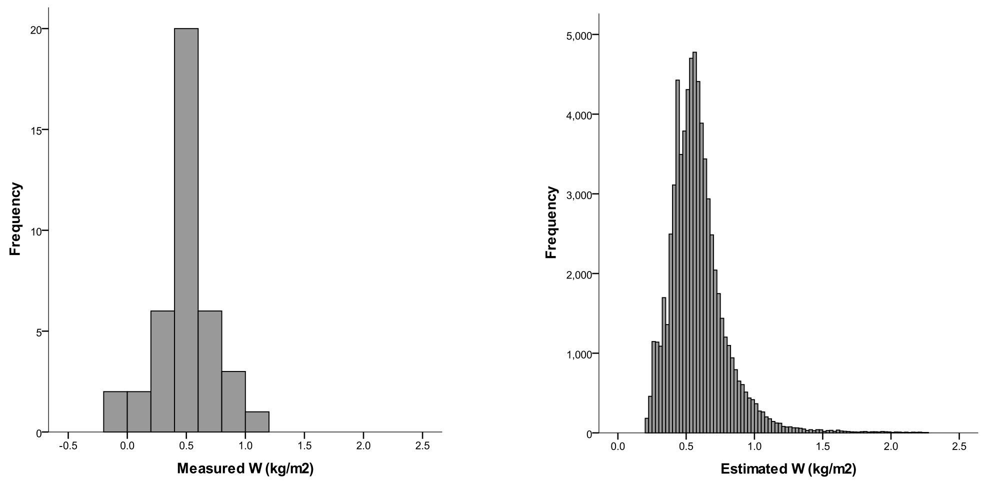

Figure 6. Mean and variability in fuel consumption estimated from WASP imagery at the landscape scale (right) and for fuel consumption measured on the ground (left).

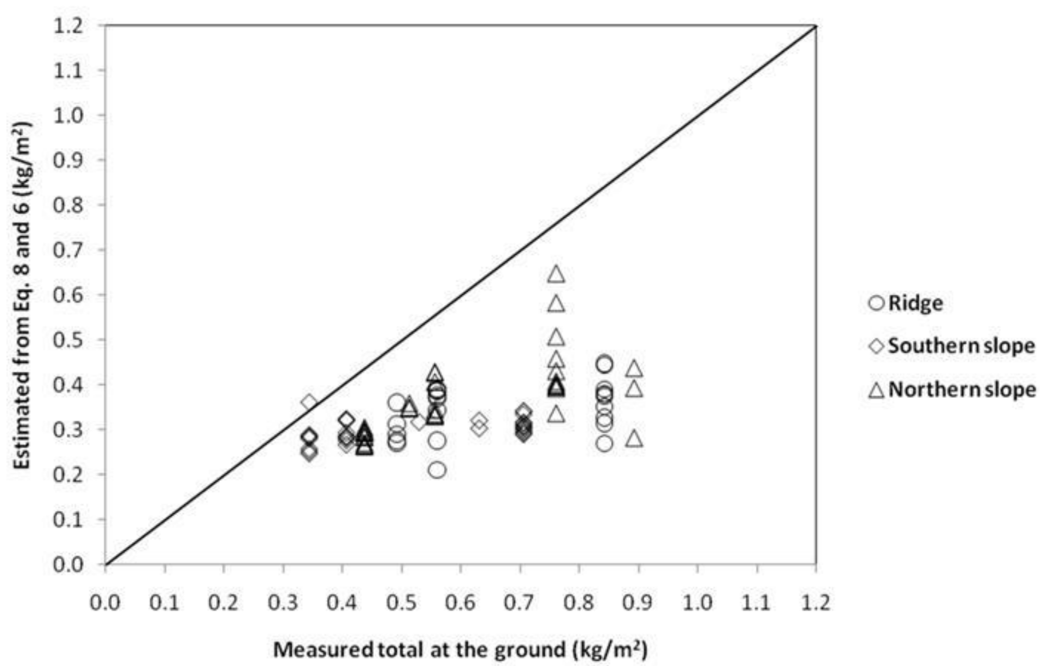

Figure 7. Pixel-to-pixel correspondence in measured and estimated fuel consumption. Fuel consumption is underestimated when it is large, a problem we are currently exploring.

MANAGEMENT IMPLICATIONS

To date, this project has had its greatest management relevance through its role in facilitating the development of the Ohio and Kentucky smoke management processes. Facilitation was accomplished through two workshops. The first workshop brought together key fire management staff from Federal, State, Private, and non-governmental organizations in Ohio and Kentucky to boost smoke management skills and begin development of plans that would satisfy the US EPA relative to smoke emissions from prescribed fire programs. Training focused on the Digital Photo Series, CONSUME, and FEPS and involved a field day. The second, follow-up workshop brought together the same fire management staff to continue training on smoke management tools and to finalize smoke management plans. Training was focused on CONSUME and V-SMOKE. Ohio developed a Smoke Management Plan and formed a Prescribed Fire Council as a means of meeting its regulatory requirements. Kentucky organized a Prescribed Fire Council in order to facilitate information sharing and reporting.

We have yet to meet our goal of using aerial infrared remote sensing to provide well validated fuel consumption maps that would provide improved estimates for smoke management efforts. Our work on this issue is continuing and advances are expected as papers that are in review and in progress are completed.

FUTURE WORK NEEDED

- Future work should be conducted on integrating a range of active-fire measurements for the purpose of closing the fire heat budget across a range in fuel types and fire behavior. This is important because knowing how much energy is produced from combustion and how it's dissipated is central to using remote sensing to estimate radiant, convective, and latent (water vapor) heat release and soil heating. The Integrated Measurements call for proposals has the potential to advance this area of fire science significantly.
- The use of unmanned aerial vehicles (UAVs) for fire monitoring should be pursued in order to obtain infrared imagery at a higher frequency than is possible in piloted aircraft. Piloted, fixed-wing aircraft are limited to a return time of ~3 minutes resulting in a large sample of fire radiated energy, but not continuous spatial and temporal coverage. UAV technology will be tested at the 2011 Prescribed Fire Combustion-Atmospheric Dynamics Research Experiments (Rx-CADRE). Ground-based calibration from fuel sampling and ground-based measurements will continue to be required until confidence in the remote sensing methods is sufficiently high.

KEY DELIVERABLES

Type	Status	Description
Workshop	Completed	Ohio and Kentucky Smoke Management Workshop and Training Session, Shawnee State Forest, Ohio, 28 November to 1 December, 2006.
Workshop	Completed	Ohio and Kentucky Smoke Management Workshop and Training Session, Maysville Conference Center, Maysville, Kentucky, 29-30 January, 2007.
Workshop	Delivered	Kremens, R. L. WASP-Lite data collection, April 20, 2007: Tar Hollow, Ohio. Cumberland Plateau Prescribed Fire Workshop, Slade, KY, 11-13 August 2008.
Presentation to managers	Delivered	Dickinson, M. B. "Fuel consumption and smoke emissions from prescribed burns in mixed-oak forests." Oral presentation at the Wayne National Forest annual fireline refresher course, Jackson, Ohio, 2 February, 2007.
Presentation to managers	Delivered	Dickinson, M. B. Fire behavior and effects monitoring. Michigan Prescribed Fire Council Annual Meeting, 5 September 2008.
MS Thesis	Completed	Suciu, L. G. 2009. Microclimatic and Topographic Controls of Fire Radiative Energy in Southeastern Ohio. MS Thesis, Ohio University.
Refereed publication	Published	Kremens, R. L., Smith, A. M. S., and Dickinson, M. B. 2010. Fire metrology: current and future directions in physics-based measurements. Fire Ecology 6:13-35.
Refereed publication	Published	Bova, A. S., Dickinson, M. B. 2008. Beyond 'fire temperatures': calibrating thermocouple probes and modeling their response to surface fires in hardwood fuels. Canadian Journal of Forest Research 38:1008-1020.
Refereed publication	In review	Kremens, R. L., Dickinson, M. B., Bova, A. S. 2010. Radiant power, energy, and fuel consumption in mixed-oak forest surface fires. International Journal of Wildland Fire, in review.
Refereed publication	Internal review	Suciu, L. G., Young, V. L., Kremens, R. L., Dickinson, M. B., Bova, A. S. 2010. Estimation of fire radiative energy and fuel consumption in prescribed fires using aerial infrared imagery. Internal review.
Refereed publication	Work in progress	Topographic controls on fire heat release and fuel consumption in mixed-oak forests in the eastern US. In preparation.

LITERATURE CITED

Dickinson, M. B. 2006. Fire in Eastern Oak Forests – Delivering Science to Land Managers. Proceedings from a 15-17 November, 2005, conference, Columbus, Ohio. US Forest Service, General Technical Report NRS-P1.

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